N75-19224

NASA CR-132608

FUEL CONSERVATION POSSIBILITIES FOR TERMINAL AREA COMPATIBLE AIRCRAFT

May 1975

Prepared under contract no. NAS1-12018 by
Boeing Commercial Airplane Company
P.O. Box 3707, Seattle, Washington 98124

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CR-132608		

4. Title and Subtitle	5. Report Date
FUEL CONSERVATION POSSIBILITIES FOR TERMINAL AREA COMPATIBLE AIRCRAFT	May 1975
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
BCAC Preliminary Design Department	D6-22421
	10. Work Unit No.
9. Performing Organization Name and Address Boeing Commercial Airplane Company (BCAC) P.O. Box 3707 Seattle, Washington 98124	11. Contract or Grant No. NAS1-12018
	13. Type of Report and Period Covered Contractor Report—Final
12. Sponsoring Agency Name and Address Langley Research Center National Aeronautics and Space Administration Hampton, Virginia	14. Sponsoring Agency Code

15. Supplementary Notes

This document supersedes issue dated March 1975.

16. Abstract

Design features and operational procedures are identified, which would reduce fuel consumption of future transport aircraft. The full fuel-saving potential can be realized during the last decade of this century only if the necessary research and technology programs are implemented in the areas of composite primary structure, airfoil/wing design, and stability augmentation systems. The necessary individual R&T programs are defined.

The sensitivity to fuel usage of several design parameters (e.g., wing geometry, cruise speed, propulsion, etc.) is investigated, and the results applied to a candidate 18 140-kg (40 000-lb) payload, 5556-km (3000-nmi) transport design. Technical and economic comparisons are made with current commercial aircraft and other advanced designs.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Terminal area TAC/Energy Fuel conservation ATT TAC	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	\229	

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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1.0 SUMMARY

This study resulted in (1) the identification of aircraft design and operational characteristics that would improve the fuel consumption of aircraft sometime during the 1980-2000 time period, and (2) the necessary research and technology (R&T) efforts needed to make those characteristics possible. (Note, many of the features of the advanced airplanes considered in the study will not be available during the first decade of this period and will not be available at all unless necessary research and technology advancement is pursued on such items as composite primary structure, advanced airfoil-wing design, and stability augmentation systems.) The study followed a similar analysis made during 1973 that emphasized design and operational characteristics that would improve congestion, noise, and emissions in the terminal area.

The study was conducted in two parts. The first part, *Sensitivity Studies,* consisted of several individual studies that investigated isolated design parameters (wing geometry, speed, propulsion, etc.) to determine their sensitivity to fuel usage. During the second part, *Concept Definition and Evaluation,* results of the sensitivity studies were applied to a candidate 18 140-kg (40 000-lb) payload, 5556-km (3000-nmi) design range airplane. The resulting design was then evaluated against three comparison aircraft. The evaluation included technical and economic comparisons with current and other advanced designs, in addition to the definition of required R&T.

The study was conducted with the assistance of three subcontractors who provided advisory, analytical, and critique support throughout the study. The subcontractors were American Airlines, United Air Lines, and Pratt & Whitney Aircraft.

Key results of the sensitivity and the concept definition and evaluation parts of the study are summarized below. The reader is cautioned that the results are applicable to a four-engine, 18 140-kg (40 000-lb) payload, 5556-km (3000-nmi) range configuration arrangement and the specific assumptions that were applied during the study. Different results and conclusions would undoubtedly be present for other missions, configuration arrangements, and assumptions.

1.1 PART I: SENSITIVITY STUDIES

Figures 1 and 2 show the summarized results of the individual sensitivity studies. Key results with respect to a 5556-km (3000-nmi) range, 18 140-kg (40 000-lb) payload, four-engine transport were determined to be:

1. As a function of detailed-wing characteristics (wing sweep and thickness ratio), up to 16% reduction in relative fuel usage can be expected from an aspect ratio (AR) 12 four-engine transport designed for a cruise speed of M = 0.8 as compared to one designed for M = 0.9. An additional reduction of up to 4% can be attained at M = 0.7; however, the impact of the lower speed on the air transportation system and airline operations would be large. Speed reductions to M = 0.7 or lower should, therefore, only be considered if extreme fuel shortages appear. No drastic economic effect over the speed range M = 0.7 to M = 0.8 was found.

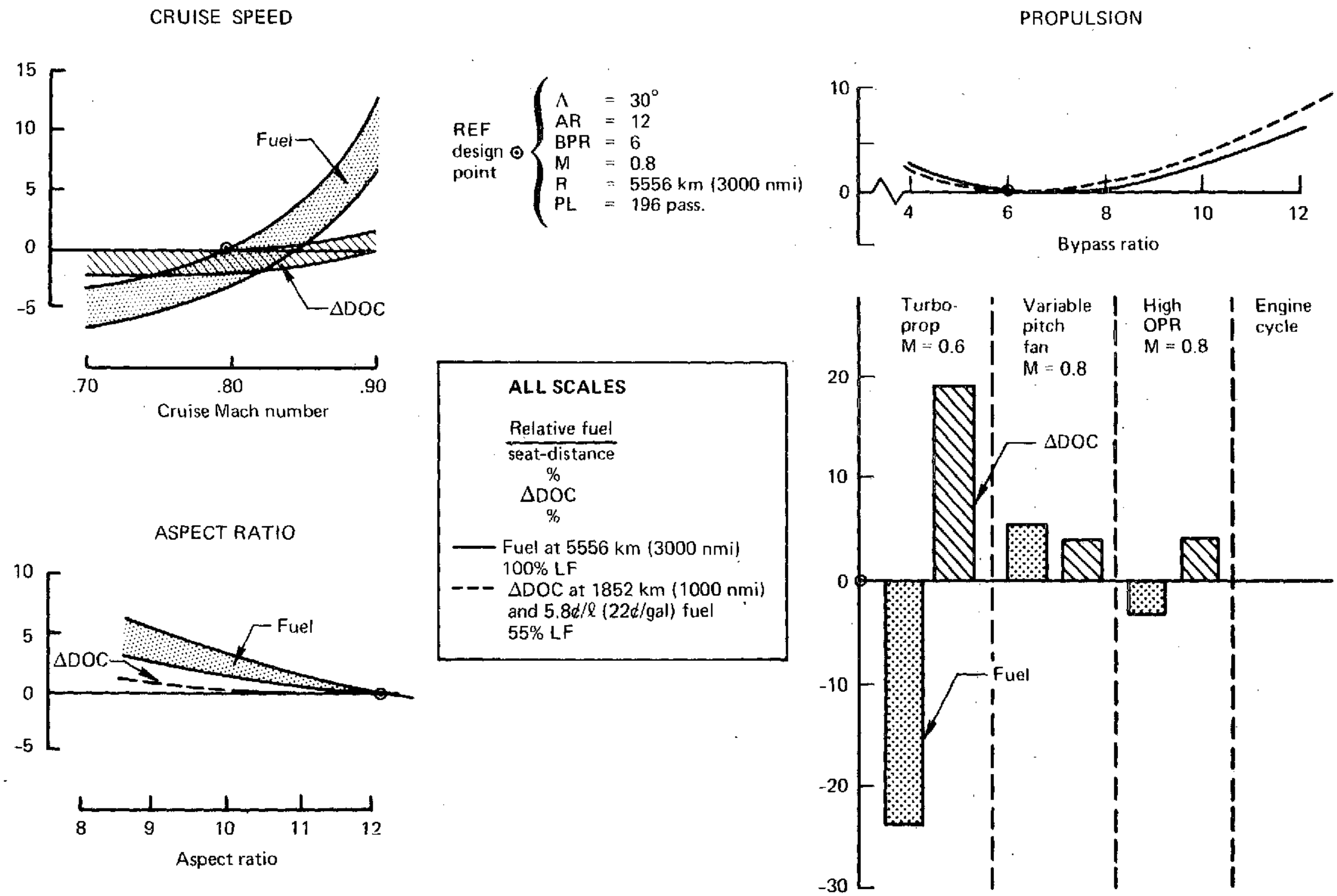

Figure 1.—Sensitivity Studies Key Results

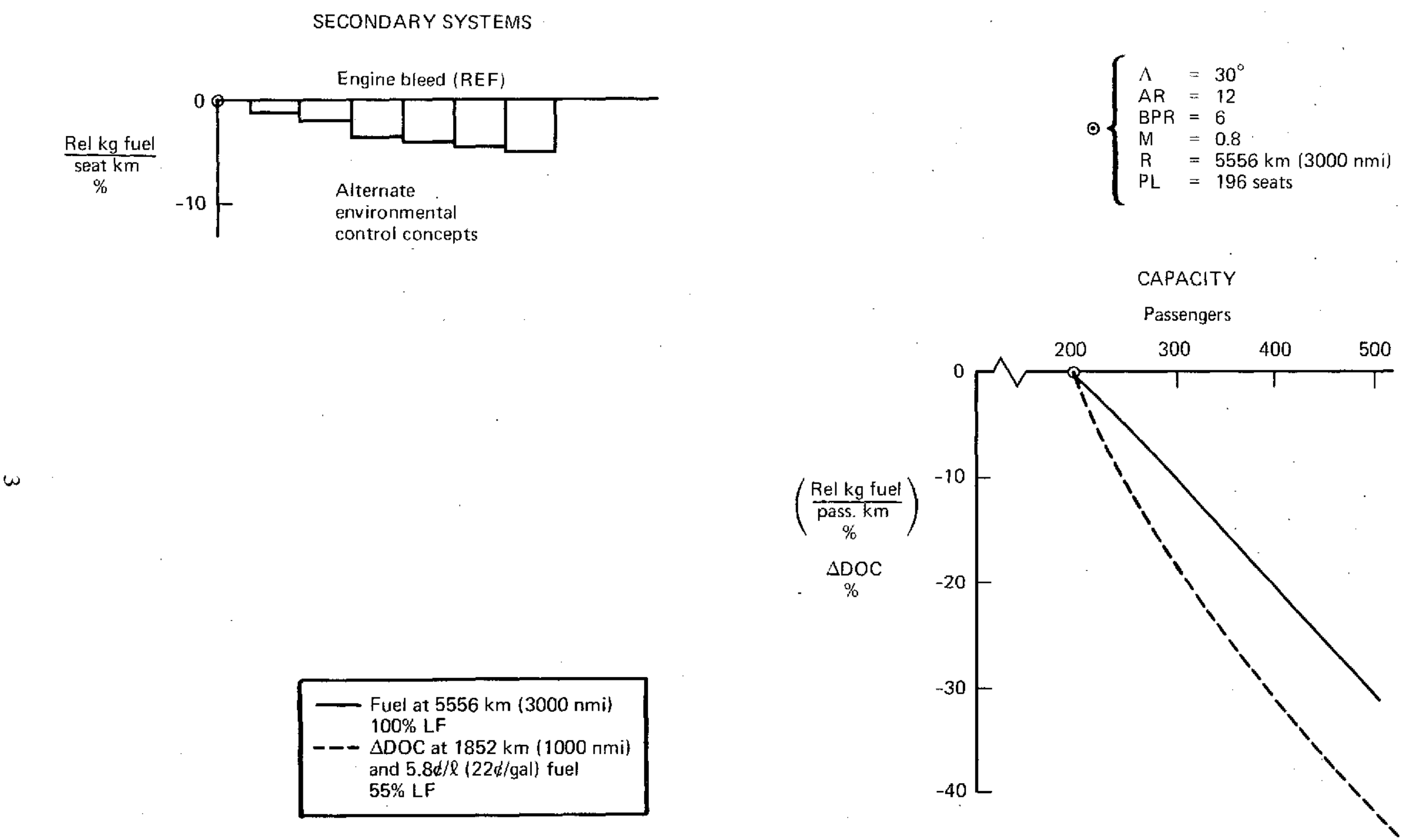

Figure 2.—Sensitivity Studies Key Results

2. Increased wing AR from 8.6 to 12 results in a reduction in fuel usage of up to 6% for a Mach 0.80 transport. Flutter penalties are present on aluminum wings with an AR of 12 for a four-engine concept. The flutter requirements could be met for an AR-12 wing with only a small weight penalty by using advanced materials. Additional fuel savings may be present above AR 12; however, flutter penalties would increase, and the airport logistics for such high AR wings on large aircraft would be difficult. Very small wing boxes are present on even the AR-12 wing, making engine mounting and control surface integration a challenge. Detail design is necessary to validate this aspect of the study. The economic evaluation favored the high (AR = 12) design.

3. With constraints of takeoff field length of 2530 m (8300 ft) and approach speed of 69 m/s (135 kn), a conventional turbofan engine with a bypass ratio (BPR) of 7 proved optimum for fuel usage with virtually no penalty at BPR = 6 or 8. The economic evaluation showed that BPR = 6 was optimum.

4. Preliminary evaluation of the airplane matched with characteristics of three alternate engine cycles, resulted in the following fuel usage and economics when compared with a BPR 6 conventional turbofan:

   a. *High Overall Pressure Ratio* (Mach cruise = 0.8).–Approximately 3% decrease in fuel consumption and 3% increase in direct operating cost (DOC).

   b. *Variable-Pitch Cycle* (Mach cruise = 0.8).–Approximately 4% increase in fuel consumption and 3% increase in DOC.

   c. *Turboprop* (Mach Cruise = 0.6).–Approximately 24% decrease in fuel consumption. The reduced productivity of the slower Mach 0.6 design resulted in an increased DOC of about 19% for this engine cycle concept.

5. Evaluation of the secondary systems indicated only very small gains in fuel reduction could be achieved in the electrical and the hydraulic systems. Alternate methods of providing air-conditioning and other pneumatic services, however, show the potential for savings up to 3% in block fuel with an increasing complexity impact on the system.

6. Increasing the size of aircraft from the 196-passenger airplane configuration to 350- and 500-passenger capacity would result in fuel savings of 15% and 29%, respectively, provided that adequate load factors and frequency could be ensured. The improvements in economics in terms of cost per seat kilometer (nautical mile) were found to be even more dramatic; however, the increase in cost per flight for the larger aircraft is of the same magnitude and, if low load factors were present, both fuel/passenger and economic advantages would deteriorate.

7. Evaluation of operations over the flight profile showed that:

   a. At the 5556-km (3000-nmi) design range, over 80% of the block fuel is used during cruise with approximately 15% and 2% being used during climb and descent approaches, respectively. Fuel for cruise reduced to 57% of the block fuel and for an average stage length of 1852 km (1000 nmi) indicates that emphasis should be placed on the climb portion of the mission and on the optimization of aircraft for shorter design range.

b. Current rules require reserve fuel equivalent to approximately 28% of the total block fuel for the 5556-km (3000-nmi) design mission. At 1852-km (1000-nmi) average stage length, reserve fuel equivalent to 70% of the block fuel is required. At 1296 km (700 nmi), the reserves and block fuel are equal. This would indicate that review and possible modification of reserve requirements in light of current air traffic control (ATC) and aircraft capability, alternate field availability, and other factors are in order.

c. Block fuel savings of 2% and over 5% at stage lengths of 5556 km (3000 nmi) and 1852 km (1000 nmi), respectively, were found to be possible by reducing the climb speed from 193 m/s (375 kn) to 154 m/s (300 kn). This resulted in a limited (1% and 2%) increase in block time for the two missions.

d. Optimum fuel use during cruise is obtained when altitude is increased proportional to the decrease in gross weight. This is approximated by a single-step climb in current practice, which yields an estimated 2% fuel penalty. Multiple-step climb could improve this cruise performance if the ATC provisions would permit.

8. Airline reaction to cruise speeds below the current M = 0.80 to 0.85 were generally negative since overall operations would be disrupted. There was an equally negative reaction to the use of Mach 0.60 turboprops on the 5556-km (3000-nmi) route because of productivity economics and passenger reactions.

1.2 PART II: CONCEPT DEFINITION AND EVALUATION

1.2.1 TAC/ENERGY CONCEPT

With NASA concurrence, an 18 140-kg (40 000-lb) payload, 5556-km (3000-nmi) design range, four-engine transport was defined, which included fuel conservation and terminal area compatibility features. Key features included:

1. *For Fuel Conservation*—Long-range cruise $(M \times L/D)_{MAX}$ at M = 0.8. AR 12, wing sweep 25°, wing thickness ratio 8%, BPR 6 (turbofan), and an environmental control system using a vapor cycle with 50% recirculation. Operational features included a 154-m/s (300-kn) climb speed and a single 4000-ft step climb during cruise, as per current practice.

2. *For Terminal-Area Compatibility*—High capacity brake system, high-speed turnoff gear, programmed flaps to attenuate wake turbulence formation, advanced electronics and displays to improve runway acceptance rate, powered wheels and advanced combustors to improve emission characteristics. Additional requirements included low 62-m/s (120-kn) approach speed for runway acceptance improvement, 6°/3° glide slope to minimize approach noise, and 8° takeoff gradient to reduce takeoff noise using peripheral acoustic lining in the engine inlet and fan duct.

This TAC/Energy concept also incorporates advanced structural materials (unidirectional composites and bonded aluminum) that could be made available for 1985 operational use, as well as stability augmentation systems suitable for flight at neutral stability. The concept, therefore, includes considerable advanced technology with attendant risk relative to achieving full predicted potential.

1.2.2 COMPARISON CONCEPTS

Three additional transport concepts were defined for comparison with the energy and TAC features of the TAC/Energy concept. These additional concepts were designed to the same payload and range requirements. Key features of the three concepts were:

1. *Current Wide-Body (CWB-E) Concept*—Three-engine, current technology (aluminum) structure but sized and operated at optimum climb and a long-range cruise speed of M = 0.82 for minimum fuel.

2. *Advanced Transport Technology (ATT-E) Concept*—Performance calculated at optimum climb and long-range cruise speeds (M = 0.88). Performance based on contractor's latest aerodynamic data. The four-engine configuration incorporated advanced composite structures, a full-time stability agumentation system compatible with a 1985 operational period, and two rings and a splitter in the nacelles for noise attenuation.

3. *Terminal-Area Compatibility (TAC-E) Concept*—Same as the ATT-E concept, but including features to minimize congestion, noise, and emissions in the terminal area.

Evaluation of fuel use characteristics of the TAC/Energy concept, compared to a transport utilizing current wide-body technology, was made by two methods as shown in figure 3.

Method I (CWB-E) utilizes a current wide-body technology aircraft sized to fly the design range/payload at a long-range cruise speed of M = 0.82 (for minimum fuel use), shown by the left side of figure 3 as a point of comparison. The TAC/Energy concept offers a maximum fuel reduction advantage of 36% by this method. The advantage can be attributed wholly to application of advanced technology to achieve airplane efficiency and delay reduction when compared to a current technology aircraft with no sizing constraints.

As a point of comparison, Method II (CWB) utilizes a current wide-body technology aircraft sized to meet the design/payload requirements at minimum cost cruise speed of M = 0.85 but is operated at a long-range cruise speed of M = 0.82, per current practice. A higher gross-weight comparison airplane with higher fuel consumption results from this method as compared to that from Method I. At long-range cruise speed it can, however, exceed the design range by approximately 5%. As shown by the right portion of figure 3, the TAC/Energy concept offers a maximum fuel reduction advantage of 38% by this method. The advantage is attributable to application of advanced technology when compared to current technology aircraft that cannot be resized for the design mission.

Tables 1 and 2 provide a summarized comparison of the ATT-E, TAC-E, and TAC/Energy concepts relative to the current wide-body technology (CWB-E) concept, considering

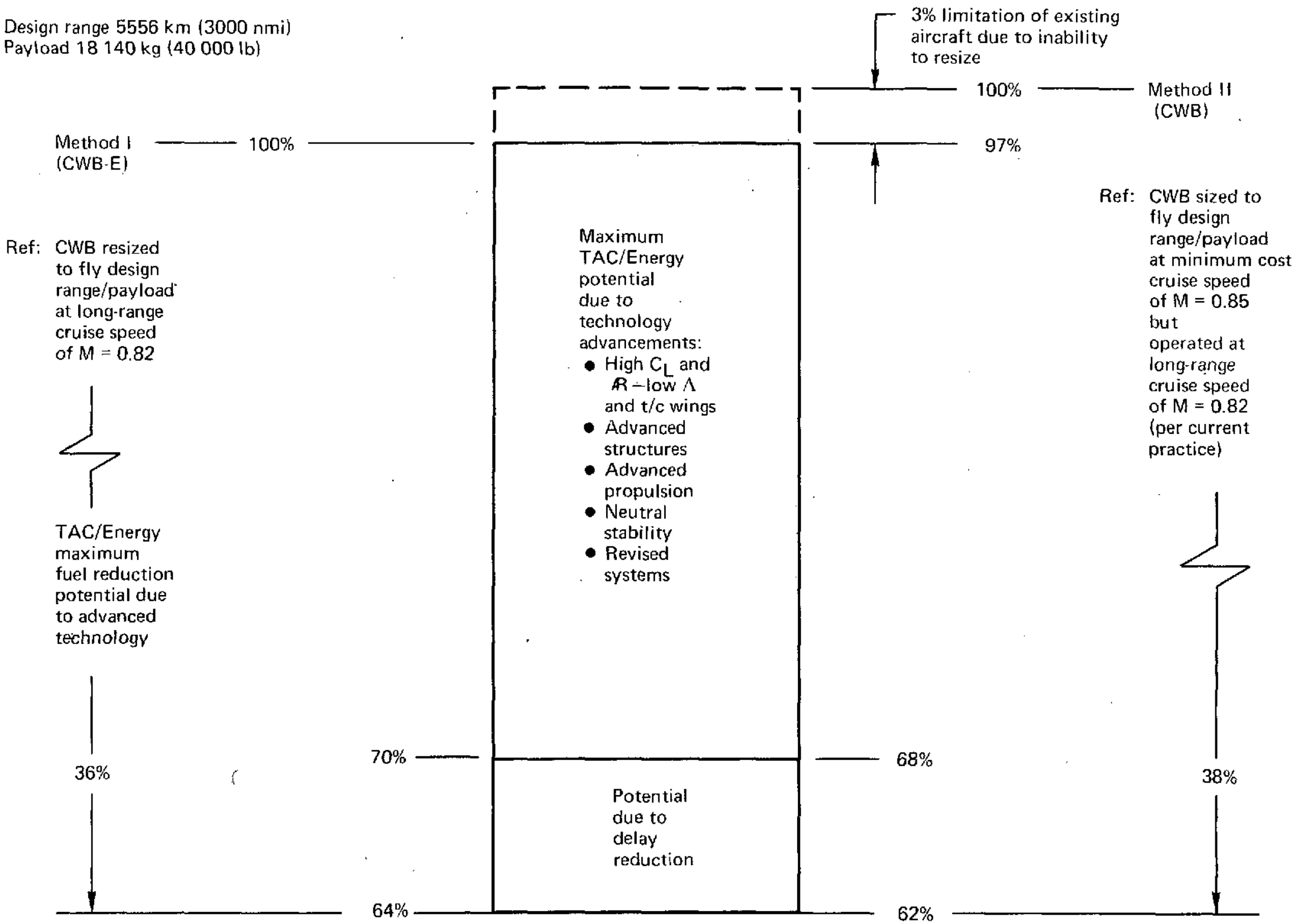

Figure 3.—Maximum TAC/Energy Fuel Reduction Potential Summary 1852 km (1000 nmi) Stage Length

Table 1.—Summarized Comparative Evaluation Results

Configurations	CWB-E M = 0.82	ATT-E M = 0.88	TAC-E M = 0.88	TAC/Energy M = 0.80
Relative airplane characteristics TOGW—relative 5556 km (3000 nmi) design range	1.0	0.90	0.96	0.78 min
Airplane economics at 1852 km (1000 nmi) and 55% load factor Relative DOC	1.0	0.94	0.94	0.86 min 0.94 max
Net present value relative dollars	1.0	1.85	1.90	1.95 min 2.40 max

R&T required (ATT-E, TAC-E, TAC/Energy)
see recommendations
(sec. 8.0)

Table 2.—Summarized Comparative Evaluation Results

Configurations	 CWB-E M = 0.82	 ATT-E M = 0.88	 TAC-E M = 0.88	 TAC/Energy M = 0.80
Projected airport impact Congestion Relative peak hour delay time typical airport	1.0	1.0	0.16	0.16
Noise Relative 90 EPNdB area noise exposure	1.0	0.68	0.54	0.39
Emissions Relative total pollutant	1.0	0.5	0.2	< 0.2
Mission fuel use—relative 5556 km (3000 nmi) stage length 100% load factor	1.0	0.92	0.87	0.64 min 0.75 max

R&T required (ATT-E through TAC/Energy)
see recommendations
(sec. 8.0)

terminal area, fuel use, and economic characteristics. The values shown by tables 1 and 2 and the points immediately following are, therefore, based on the previously noted Method I CWB-E evaluation approach.

The values shown in tables 1 and 2 reflect a minimum and maximum range of comparative fuel use for the TAC/Energy concept relative to the CWB-E. The range is based on a judgmental evaluation that considers the 64% maximum potential (including delay reduction) versus what could likely be achieved (75% minimum) in an integrated design acceptable to airport operators. Additional conclusions reached during the study with regard to comparative fuel use potential relative to the CWB-E, ATT-E, and TAC-E comparison aircraft were:

1. When compared to an aircraft that reflects current wide-body technology, figure 4 shows three categories of potential fuel reduction, that are a function of the cost and time associated with the R&T required to achieve the potential. These categories are:

   a. Technology that is now available cannot be included on current wide-body aircraft but could be included on new near-term transports. Estimates for this category can be made with high confidence to provide a nominal 10% reduction with a limited tolerance on the estimate.

   b. Nominal advancements in the technology areas are listed in figure 4 and with adequate R&T could be operationally realized around the 1985 time period. This category covers the subjects included on the TAC/Energy configuration, which is estimated to reflect a nominal 25% reduction. It could yield as much as 30% reduction if all calculated potential could be realized or as low as 23% because of design limitations during incorporation into a practical design that would be acceptable to operating airlines. An additional 6% reduction is potentially available if the delay reduction potential of the TAC/Energy reduction can be realized. This additional 6% also requires adequate R&T, and the majority of the fleet must include TAC features.

   c. Further advancements in several technology areas are noted on the lower portion of figure 4, the R&T for which can be expected to delay their implementation until the 1990-2000 time period. A nominal fuel-reduction potential of up to 50% is foreseen if the nominal potential of all items in figure 4 can be realized; however, the estimate tolerance is quite large.

2. When compared to the TAC-E concept, the TAC/Energy shows advantages of 18.7% in takeoff gross weight (TOGW), 9% in economics, and 29% (maximum) in fuel use for the design mission. The 90-EPNdB noise contour during approach of the TAC/Energy concept is not as good, but the overall area is less mainly because of lower sideline noise due to higher BPR engines and smaller engine size. The approach noise could be improved by use of further noise attenuation but with weight, economic, and fuel use penalties.

3. When compared to the ATT-E, a reduction of 30% (maximum) in fuel use in addition to the same improved terminal-area compatibility characteristics is offered by the TAC/Energy concept.

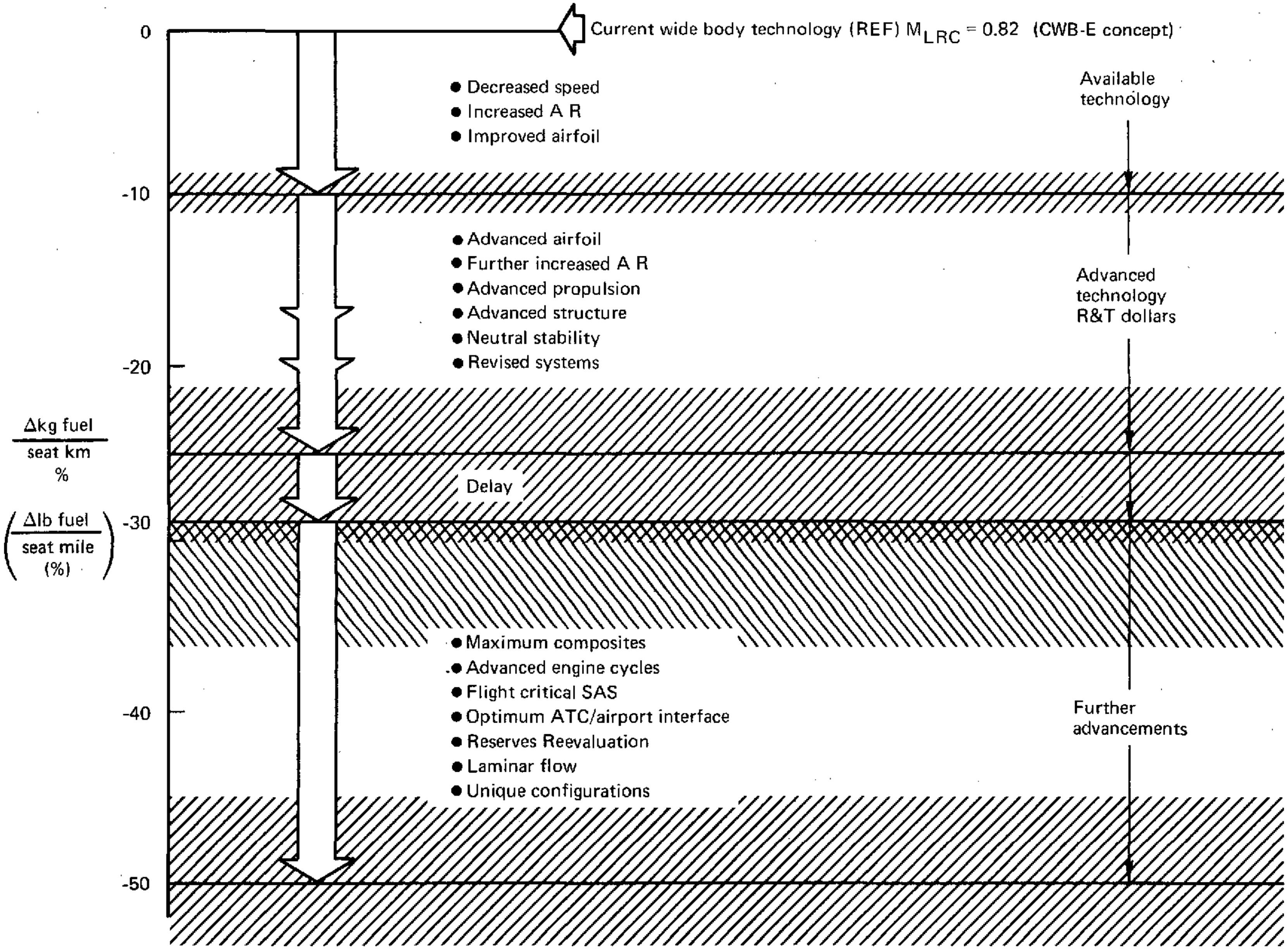

Figure 4.—Fuel Use Reduction Potential Categories

The key conclusions reached as a result of the study were:

1. Future aircraft incorporating desirable features of the ATT and TAC aircraft, in addition to advanced aerodynamic technology (higher AR, lower sweep angle and thickness wings, increased engine BPR, improved environmental control, lower cruise speeds, and climb/cruise operational techniques), offer a maximum potential of 36% less fuel use with acceptable noise and much better delay and emission characteristics than current wide-body transports that are sized and operated at long-range cruise speeds. Of this 36%, 6% is due to advanced materials; 18% to advanced propulsion and more efficient wing aerodynamics (sweep, aspect ratio, etc.) based upon a very limited amount of airfoil data in the cruise C_L range; 2% to reduced cruise speed; 1% to flight at neutral stability; 3% to improved environmental control systems; and 6% to elimination of costly delays. Final R&T results and application to a transport design acceptable to airline operators could erode the calculated 36% total potential to as low as 25%.

2. The general direction that future transport design should take when considering energy as a driving force depends on the situation that could be expected to exist. Two major possibilities with the design trends that appear attractive are as follows:

   a. *Fuel Available but at High Cost.*—The design approaches for efficient economical operations and significant reduction in fuel use are high AR, reduced wing sweep and thickness, and subsystem improvements. Airplane size should be chosen as a function of the market with attempts made to increase load factors without significantly degrading service.

   b. *Significant Shortage of Fuel.*—The design approach that would yield further significant reductions in fuel use but with major disruption to the air transportation system with subsequent economic penalties would include the same design characteristics noted above, plus further reductions in cruise speed and the use of larger capacity transports with frequency reductions to maintain high load factors.

3. Major R&T advancement was needed in the following areas:

   a. A comprehensive data base is needed covering parametric design data over a range of AR's 8 to 14, thickness ratios 6% to 14%, and Mach numbers 0.7 to 0.85 with wing sweep consistent with the Mach number. This should include both two- and three-dimensional testing for high-lift (0.5 and 0.6) coefficient airfoils and wings. This should be developed in a parametric form so that industry could select proper airfoil and wing characteristics that would fit particular situations existing in the future.

   b. Current work on wake vortex dissipation with minimum weight and loss of aerodynamic efficiency should be expanded.

   c. The potential of alternate engine cycles should receive further detailed evaluation including application to short-range aircraft.

d. Alternate environmental control systems deserve attention.

e. Studies are needed with respect to reserve rules and aircraft/ATC interface throughout the flight profile as affecting fuel use.

f. A similar study that emphasizes short-range aircraft is recommended since many of the conclusions with respect to BPR, wing geometry-cruise speed, and magnitude of fuel savings will be different.

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2.0 INTRODUCTION

2.1 STUDY OBJECTIVE

As shown by figure 5, the objective of this study was to determine design and operational features that could minimize the amount of fuel required to operate advanced aircraft in a commercial air transportation system. The aircraft also incorporated features needed to enhance efficiency and environmental impact performance in the terminal area. The end objective was to determine the research and technology (R&T) efforts required to make fuel conserving features available on aircraft that would be introduced to operational status during the 1980-2000 time period.

Objectives

- Explore and determine impact of fuel conserving possibilities for aircraft that also offer terminal area compatibility
  - Minimum congestion
  - Acceptable noise and emissions

  } TAC study
- Identify required research and technology

Key constraints

- CTOL – 5556 km (3000 nmi) design range
- Operational – during 1980–2000 time period

Figure 5.—TAC/Energy Study Objectives and Key Constraints

2.2 BACKGROUND

The chronology of events leading to this study are shown by figure 6. During 1971-72, studies conducted as a part of the NASA Advanced Transport Technology (ATT) program (ref. 1) resulted in the identification of several technologies that, if proper R&T were pursued, could improve the weight, cruise speed, and environmental characteristics of future aircraft during the 1980-2000 time period.

The ATT studies also resulted in the identification of congestion, noise, and emissions in the terminal area as being subjects that could limit the ability of the air transportation system to meet the demands of the future. This led to the initial TAC study (refs. 2 and 3). The TAC study also took advantage of the results from studies of potentially advanced air traffic control (ATC) systems conducted during 1971-72 under Department of Transportation (DOT) sponsorship. Requirements and design approaches resulting from the TAC study (ref. 2) are discussed in section 5.0.

During conduct of the TAC study, it was found that some of the aircraft design approaches needed for TAC were also effective in reducing fuel consumption. The intent of the current TAC/Energy effort was, therefore, to pursue previously identified items, as well as other items that offered fuel conservation possibilities.

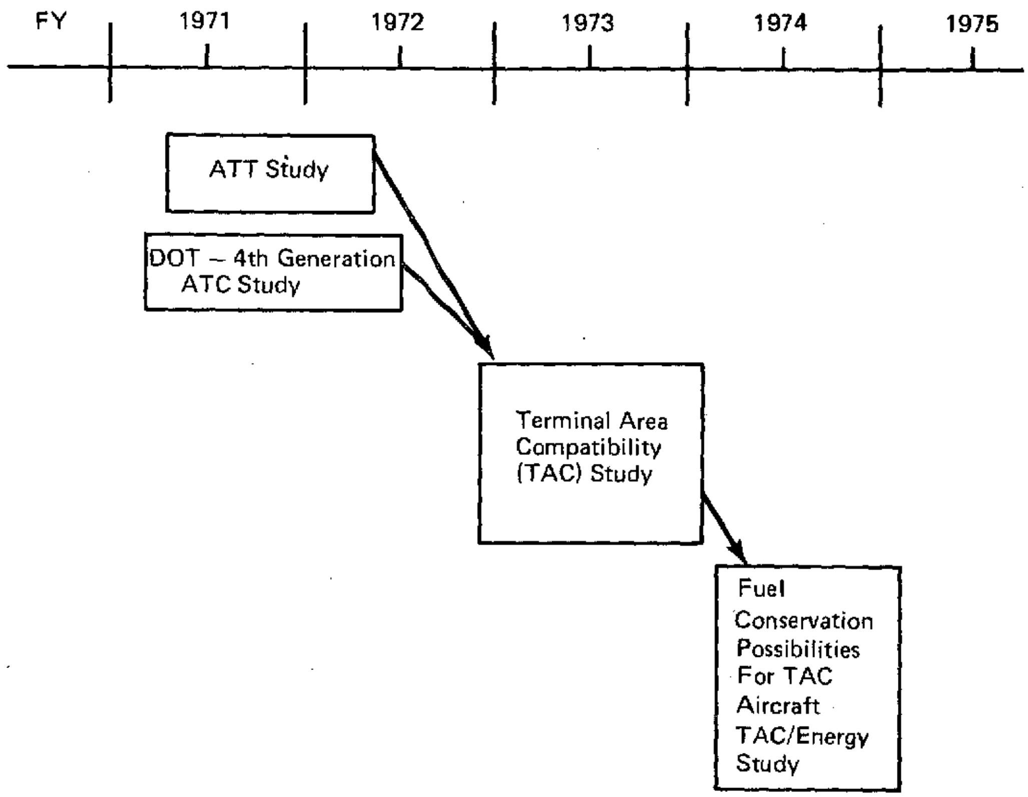


Figure 6.—Study Background

For ease of reference, key characteristics of the transport configurations resulting from the previous ATT and TAC studies, as well as this study, are shown on the foldout page at the end of this document.

2.3 SCOPE

This TAC/Energy study consisted of conceptual design and the technical and economic analysis necessary to evaluate design, operational features, and R&T programs that could improve the fuel consumption of transport aircraft. Generally, the same guidelines and requirements used for the TAC study were followed during this study. Key requirements and constraints were:

- Basic study mission (per statement of work)

    Design range—5556 km (3000 nmi)

    Design payload—18 140 kg (40 000 lb)

    Maximum field length—2530 m (8300 ft) at 305 m, 305 K (1000 ft, 90°F)

    Noise objective—FAR 36 or less consistent with minimum fuel consumption

Emissions:

Smoke–smoke number 15 or less (SAE-ARP 1179 measurement specification)

CO–20 kg/1000 kg fuel (max)

HC–4 kg/1000 kg fuel (max)

NO_x–10 kg/1000 kg fuel (at takeoff max)
(Low as feasible during ground operations)

- Air transportation system

  Current route system: domestic route system as projected to evolve over 1980-2000 time period

  Terminals: Los Angeles (LAX), Chicago, Midway (ORD), and New York John F. Kennedy (JFK) (per ref. 2)

  Air traffic control system: completion of the upgraded third-generation ATC system as defined by FAA planning (ref. 4), and the phased adoption of the fourth-generation system defined under contracts DOT-TSC-145 and DOT-TSC-306 (ref. 4)

- Evaluation time period (1980-2000 time period)

- Economic analysis

  DOC–modification of 1967 ATA equation to better reflect evaluation of an advanced aircraft

  IOC–per Lockheed report LW-70-500R (dated May 1970) modified to reflect only airplane related variables (ref. 5)

This Task VII study was conducted with the assistance of three subcontractors who provided advisory, analysis, and critique assistance through the study period. These subcontractors were:

Airlines:

American Airlines }
United Air Lines } Fleet and operations impact

Propulsion:

P&WA–State-of-the-art and preliminary cycle analysis

2.4 GENERAL STUDY APPROACH

The general approach followed is shown in logic diagram form in figure 7. Two major categories of work were involved: (1) sensitivity studies, and (2) concept definition and evaluation. These are briefly described in the following two sections.

2.4.1 SENSITIVITY STUDIES

A series of individual studies were conducted using the basic TAC configuration that resulted from reference 2. Variations to several technical and operational features of that configuration were evaluated with the objective of determining the most attractive characteristic of each variable from the standpoint of effect on fuel use. The results provided a measurement of the sensitivity of each variable as to effect on fuel use. The variables evaluated were:

- Wing geometry (wing aspect ratio, thickness ratio, sweep angle, and cruise Mach number)
- Turbofan bypass ratio
- Secondary systems
- Operations (payload/frequency/load factor, climb/cruise/descent flight profile, and reserves)
- Alternate engine cycles

Although figure 7 indicates that the above studies were conducted in parallel, it was necessary to pursue some of them in series. For example, the wing geometry study was conducted first to establish the cruise Mach number and AR that were used for the BPR and payload studies. Additional details in this respect are contained in section 4.0.

Results of the individual sensitivity studies were correlated and combined with reevaluation of design methods to meet the terminal-area compatibility (TAC) goals established during the TAC study (ref. 2). The combined results were presented to NASA as recommendations for design features to be included in the transport concept for consideration during the rest of the study. Key design features included in those recommendations are shown in figure 8. A summary of the work conducted to that point is provided in section 4.0.

2.4.2 CONCEPT DEFINITION AND EVALUATION

Following receipt of NASA approval, the remaining study effort was devoted to defining and evaluating an example 18 140-kg (40 000-lb) payload, 5556-km (3000-nmi) transport that incorporated the recommended characteristics.

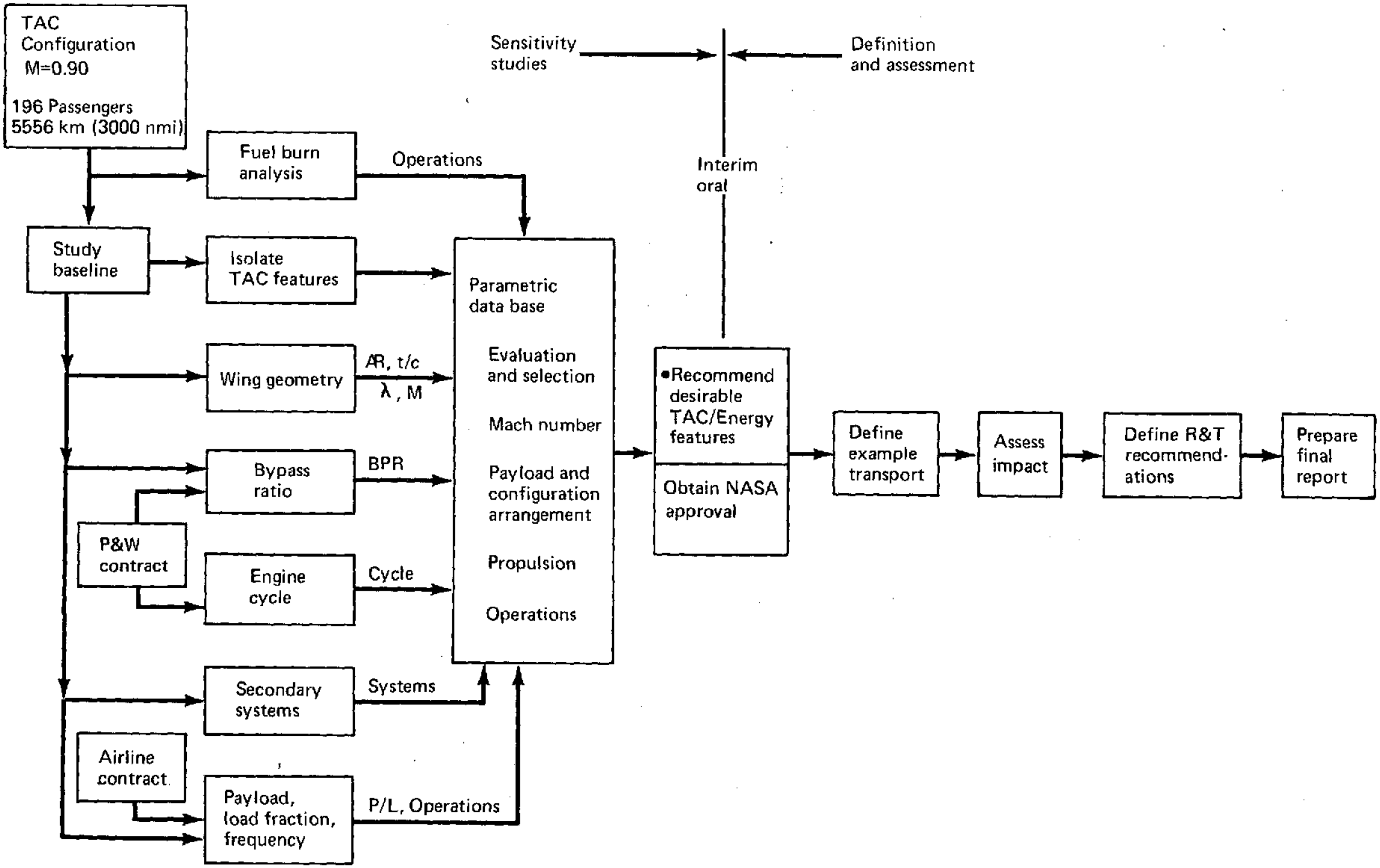


Figure 7.--Study Approach Logic

- Basic design, 18 140 kg (40 000 lb) payload 5556 km (3000 nmi) design range
  - Long range cruise: Mach = 0.8
  - Æ = 12, sweep = 25°, t/c = 0.08
  - Four engines, BPR = 6, OPR = 24
  - Advanced structures and active controls
- Add terminal area compatibility features as previously identified
- Evaluate technical and economic impact
  - Fuel use
  - Terminal area goals
  - R&T requirements
- Provide advisory inputs for R&T on
  - Larger aircraft
  - Unconventional engines

Figure 8.—Definition and Assessment Phase—Design Features

The final configuration, referred to as the TAC-Energy configuration, was evaluated with respect to fuel use and economics and compared to the previously defined CWB-E, TAC-E, and ATT-E. Results of the technical and economic evaluation are contained in section 6.2.

Final evaluation consisted of reviewing the state of the art relative to the technical demands for fuel conservation. The TAC/Energy configuration was used as the base for this evaluation. Where deficiencies were found, recommended R&T programs including cost and schedule were developed. These recommendations are contained in section 8.0.

3.0 ABBREVIATIONS AND SYMBOLS

AF	propeller blade activity factor
APL	airplane
APPR	approach
APU	auxiliary power unit
AR	aspect ratio
ASM	available seat mile
ATA	Air Transport Association
ATC	air traffic control
ATT	advanced technology transport
A_{wet}	airplane wetted area
A/C	aircraft
A/P	airplane
b	wing span
BDL	Hartford, Conneticut
BOS	Boston, Massachusetts
BPR	bypass ratio
cfm	cubic feet per minute
CO	carbon monoxide
$\bar{c}$	mean aerodynamic wing chord
c_c	local wing chord
c_{cf}	local flap chord
C_D	drag coefficient
c_f	skin friction coefficient
C_F/C	ratio of flap chord to wing chord
c_ℓ	section lift coefficient

C_L	lift coefficient
Cw	mean aerodynamic wing chord
CLE	Cleveland, Ohio
CWB	current widebody
C/B	coburning
DFW	Dallas/Fort Worth, Texas
DOC	direct operating cost
DOT	Department of Transportation
DTW	Detroit, Michigan
e	span efficiency factor
eng	engine
ECS	environmental control system
EPA	Environmental Protection Agency
EPNdB	effective perceived noise, decibels
filt	filter
FOD	foreign object damage
FPR	fan pressure ratio
FS	wing front spar
F_n	net thrust
HC	hydrocarbons
HOPR	high overall pressure ratio
hp	horsepower
HX	heat exchanger
ICAC	initial cruise altitude capability
ILS	instrument landing system
IOC	indirect operating cost

JFK	John F. Kennedy International Airport, New York, New York
kg	kilogram
km	kilometer
kW	kilowatt
KEAS	equivalent airspeed in knots
LAX	Los Angeles International Airport, Los Angeles, California
LCF	low cycle fatigue
LD GR	landing gear
LE	leading edge
LF	passenger load factor
LRC	long range cruise
L/D	lift to drag ratio; ratio of engine inlet length to compressor diameter; ratio of heat exchanger length to diameter
lb	pound
M	Mach number
m	meter
MAC	mean aerodynamic chord
MAX	maximum
M_{CR}	cruise Mach number
MEM	Memphis, Tennessee
MEX	Mexico City, Mexico
MLG	main landing gear
M_{LRC}	long-range cruise Mach number
MLW	maximum landing weight
M_d	dive Mach number
M_{mo}	maximum operating limit Mach number
n	maneuver load factor

nmi	nautical mile
NO_x	oxides of nitrogen
NPV	net present value
NYC	New York City
OEW	operational empty weight
OKC	Oklahoma City, Oklahoma
OPR	overall pressure ratio
ORD	O'Hare International Airport, Chicago, Illinois
PHL	Philadelphia, Pennsylvania
PHX	Phoenix, Arizona
PL	payload
PVD	Providence, Rhode Island
P&WA	Pratt & Whitney Aircraft
recirc	recirculation
R&T	research and technology
ROC	Rochester, New York
ROI	return on investment
RS	wing rear spar
S_w	wing area
SAN	San Diego, California
SAS	stability augmentation system
sec	second
SFC	specific fuel consumption
SFO	San Francisco, California
SLC	Salt Lake City, Utah
SLS	sea level static

SOB	side of body
SPS	secondary power system
STL	St. Louis, Missouri
TAC	terminal-area compatibility
TE	trailing edge
t/c	wing thickness-to-chord ratio, measured streamwise
TIT	turbine inlet temperature
TOC	total operating cost
TOFL	takeoff field length
TOGW	takeoff gross weight
TUS	Tuscon, Arizona
T/F	turbofan engine
T/P	turboprop engine
T/R	thrust reverser
T/W	airplane thrust-to-weight ratio
T_4	engine turbine inlet temperature
V	velocity
V_{APP}	approach speed
V_B	maximum gust intensity speed
V_C	cruising speed
V_D	dive speed
V_F	flap design speed
V_{MCA}	air minimum control speed
V_{MO}	maximum operating limit speed
V_S	stall speed
V/P	variable-pitch fan engine

VPF	variable-pitch fan
W_A'	total engine airflow
WAS	Washington, D.C.
W/S	airplane wing loading
YYZ	Toronto, Canada
δ	ratio of total pressure at engine compressor face to standard pressure at sea level
θ	ratio of total temperature at engine compressor face to standard temperature at sea level
η	spanwise wing coordinate—% semispan
Λ	wing sweep
ϵ	heat exchanger effectiveness
$\Delta P/P$	pressure loss

4.0 SENSITIVITY STUDIES

4.1 INTRODUCTION

The initial work under this contract was conducted to determine the design characteristics that should be included in the aircraft to be defined and evaluated during the latter part of the study. Several individual studies were, therefore, conducted to determine the sensitivity of aircraft fuel usage to changes in specific design parameters. This section describes these individual studies.

4.1.1 OBJECTIVES AND CONSTRAINTS

The objective of the sensitivity studies was to evaluate key airplane and engine design parameters that could minimize fuel consumption consistent with reasonable noise, emissions, congestion, and economics at a design range of 5556 km (3000 nmi). The design constraints observed were:

1. Initial cruise altitude capability $\geqslant$9144 m (30 000 ft) was selected to ensure flight above adverse weather conditions.

2. Takeoff field length $\leqslant$2530 m (8300 ft) [at 305 m, 305 K (1000 ft, 90° F)] was selected to be consistent with the previous TAC airplane for continuity and comparative purposes.

3. Landing approach speed $\leqslant$69 m/s (135 kn) at maximum landing weight was selected as representative of the approach speed required to handle wet and icy runway conditions at the design field length.

A parametric performance analysis computer program was used to determine the combination of both wing and thrust loading that resulted in airplanes that met the above range payload objectives and constraints with minimum fuel usage.

4.1.2 SCOPE OF STUDIES

Table 3 shows the scope of the sensitivity studies. Studies were carried out in the six major areas that have an impact on airplane fuel consumption. An initial operations study was conducted to determine climb and cruise flight conditions that would minimize fuel use. Results were applied to the remainder of the individual sensitivity studies. Wing geometry and cruise speed were evaluated based upon previous studies. It was expected that reducing speed from the M = 0.9 of the TAC airplane and increasing the wing AR would result in fuel savings. Mach numbers 0.8 and 0.7 and AR's from 8.6 to 12 were investigated in depth. Wing sweep angle was decreased from 37.5° to 10° as cruise speed was reduced.

To carry out the wing geometry-cruise speed study, it was necessary to select an initial engine BPR at the Mach numbers of interest (M = 0.7 and 0.8). Since a detailed engine BPR study was to be conducted later during the engine cycle sensitivity studies, a preliminary study was carried out to determine the study baseline BPR value. Parametric engine studies

Table 3.—Scope of Studies

• Wing geometry — cruise speed	$M = 0.7$ to 0.9 $AR = 8.6$ to 12.0 $\Lambda = 10°$ to $37.5°$
• Engine bypass ratio (preliminary –IR&D)	BPR 6 vs 12
• Propulsion • Conventional cycle • Advanced cycles	 BPR 4 to 12 T/P, HOPR T/F, V/P T/F
• Secondary systems	
• Airline coordination	
• Payload	196 to 500 passengers

indicated a reduction in cruise SFC with increased BPR; however, it was recognized that lower cruise SFC's might be offset by configuration effects arising from the larger engine weight and diameter. Two BPR's, 6.0 and 12.0, were considered to "bracket" the area of interest. The results of this study showed BPR 6 to be superior to BPR 12; therefore, it was selected for the wing planform-cruise speed study. With the assistance of P&WA as subcontractor, conventional turbofan cycles with BPR's from 4 to 12 were studied in comparative detail. In addition, three advanced cycles, (1) a turboprop at a cruise speed of $M = 0.6$, (2) a high (40) overall pressure ratio (OPR) turbofan, and (3) a variable-pitch turbofan, were subjected to preliminary evaluation.

The airplanes' secondary power systems are of lesser but still significant impact on fuel usage. The pneumatic (air-conditioning, etc.), electrical, and hydraulic systems were examined to determine possible energy reductions with resultant fuel savings.

Close coordination with two airlines was maintained during the sensitivity studies to ensure realism in the operational and economic assessment of the airplanes investigated. The final sensitivity study consisted of determining the effect of airplane payload size on fuel consumption and economics. Three passenger sizes (196, 350, and 500) were analyzed on a representative airline route system. The results were reviewed with the airlines.

4.1.3 REFERENCE TECHNOLOGY LEVEL

To meet the prime objective of the sensitivity studies, it was necessary to have a high level of confidence in the trend results. Therefore, a solid data base in the area of interest ($M = 0.7$ to 0.8) was mandatory. This was achieved by utilizing data available from current programs that were applicable to the speed regime of interest. The definition of technologies so selected follows.

Configuration: conventional, wide-body, low-wing, four-engine, strut-mounted

Aerodynamics: advanced airfoil for cruise, conventional curved Krueger leading-edge and double-slotted trailing-edge flaps for takeoff and landing

(The ATT airplane had a highly swept wing and cruised at M = 0.98 with a fairly low lift coefficient. Extrapolating these data to M = 0.90 for both the ATT reduced-speed airplanes and the TAC airplane was considered reasonable. However, further extrapolation of these data to M = 0.7 to 0.8 might have given misleading results.)

Flight controls: conventional sizing criteria for horizontal and vertical tails (i.e., no flight-critical stability augmentation)

Structures: aluminum (However, the influence of the use of composites where it could impact study results, i.e., wing AR, was investigated.)

Propulsion: consistent with 1980 technology freeze

Noise: peripheral lining in inlet and fan duct only (TAC study showed further noise treatment had very large fuel burned penalties.)

Systems: conventional pneumatic, hydraulic, and electrical systems

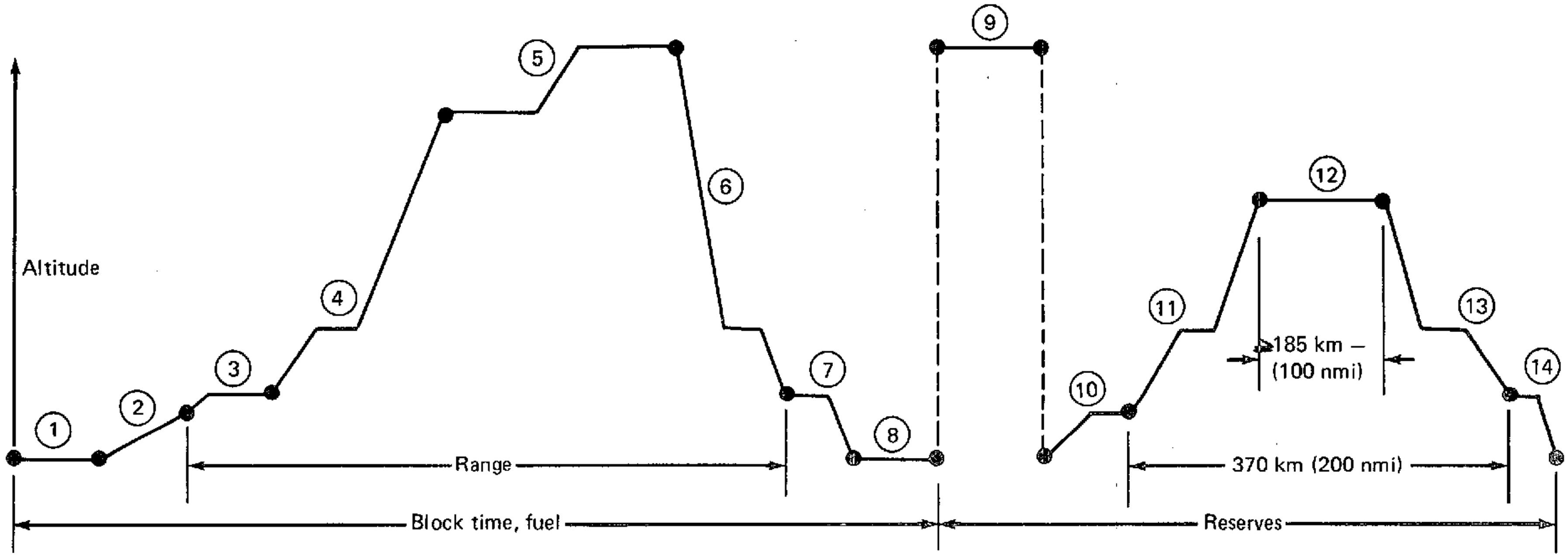
4.1.4 FLIGHT PROFILE AND MISSION RULES

The flight profile and mission rules used in the sensitivity studies are shown in detail in figure 9. The flight profile is very similar to that specified by the 1967 ATA Domestic Rules profile with the exception of a small en route cruise allowance. Reserves consisted of 1 hour at long-range cruise speed plus fuel for diversion to an alternate airfield 370 km (200 nmi) away from destination. This is equivalent to about a 1296-km (700-nmi) flight.

4.2 TAC FUEL BURN ANALYSIS AND OPERATIONAL PROCEDURES

A detailed mission analysis was conducted on the TAC airplane to determine the relative importance of each portion of the flight in terms of fuel usage. The results versus stage length are shown in figure 10. At all ranges, most of the fuel is used in climb and cruise, indicating that great emphasis should be placed on maximizing aerodynamic and propulsive cruise efficiency (L/D and V/SFC). Figure 10 also shows that at the design range the reserve fuel amounts to about 25% of the block fuel, while at the typical average stage length of only 1852 km (1000 nmi), the reserve fuel is equal to about 70% of the block fuel. If the fuel reserves could be reduced 50%, block fuel savings would be substantial, 6% at 5556 km (3000 nmi), and 7% at 1852 km (1000 nmi), since the average mission weight is reduced about 6% to 7% in each case, and fuel burned is directly proportional to average cruise weight. The effect on block fuel of varying reserve fuel from 50% to 150% of current requirements is shown in table 4.

Since most of the mission fuel is consumed in climb and cruise, particular attention (consistent with acceptable operations) was paid to the procedures used in both segments to minimize fuel burned. Figure 11 shows the effect of reducing climb speed on the TAC airplane from 193 m/s (375 kn) to 175 m/s (340 kn) to 154 m/s (300 kn) as a function of stage length. These data show that the saving in block fuel is twice as much as the block time penalty at any stage length. Based upon these data, a 154-m/s (300-kn) climb speed



(1) Taxi out (9 min.taxi thrust)

(2) Takeoff (1 min.max.thrust)

(3) Climb to 457m (1500 ft), accel to 129 m/s (250 kn)

(4) Climb to 3048 m (10 000 ft), accel to 154 m/s (300 kn), climb to cruise alt

(5) Cruise, 1219 m (4000 ft) step at mid cruise

(6) Descend to 3048 m (10 000 ft), decel to 129 m/s (250 kn), descend to 457 m (1500 ft), decel to V_{APP}

(7) ILS approach (2 min.max.thrust)

(8) 5 min.taxi in (from reserves)

(9) 1 hr at LRC altitude and M

(10) Missed approach (2 min at max thrust)

(11) Climb

(12) Cruise

(13) Descend

(14) ILS approach

Figure 9.—Flight Profile and Mission Rules

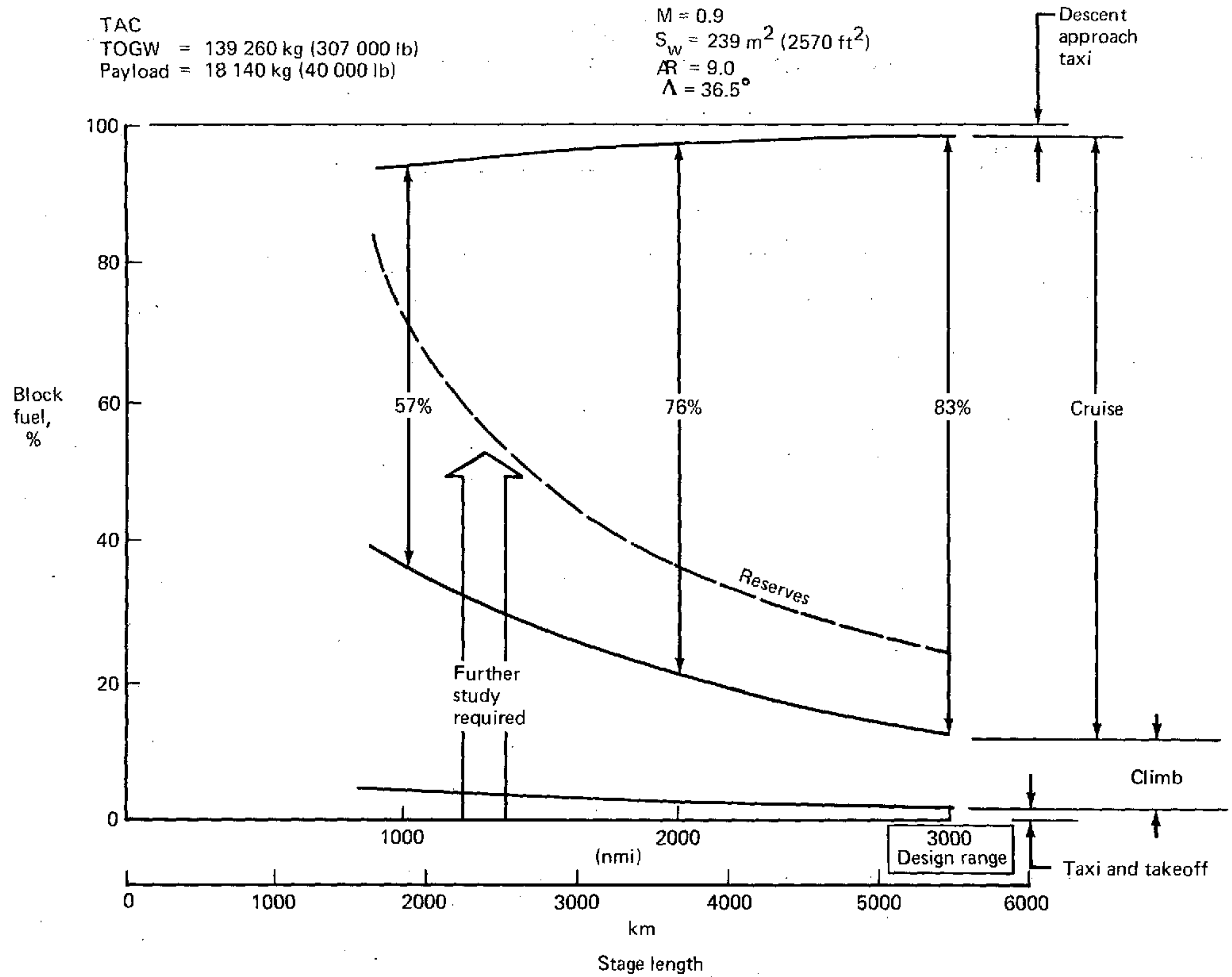


Figure 10.—Detailed Mission Analysis

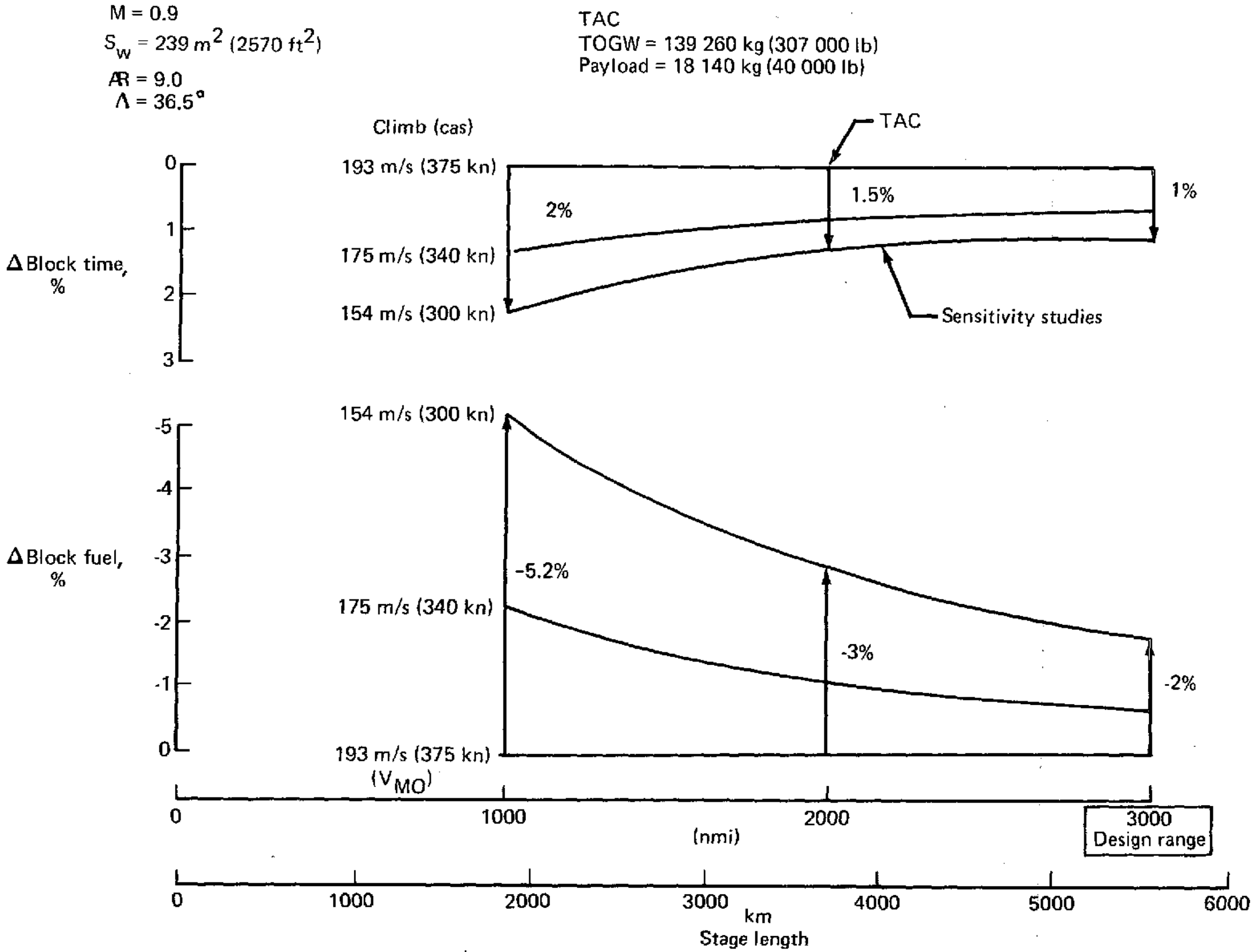


Figure 11.—Operational Techniques—Climb Speed, TAC Airplane

Table 4.—Reserve Fuel Requirements Versus Block Fuel

	Block fuel requirements	
Percent current reserve fuel requirement	Stage length 5556 km (3000 nmi)	Stage length 1852 km (1000 nmi)
50	0.940	0.935
100 (Current)	1.000	1.000
150	1.065	1.065

Design: Range 5556 km (3000 nmi), payload 18 140 kg (40 000 lb)

[129 m/s to 3048 m (250 kn to 10 000 ft)] was selected for the sensitivity studies in order to save fuel. Figure 12 shows typical effects of cruise speed and altitude on fuel mileage for subsonic jetliners. In general, the left side of this figure shows that in order to save fuel, a jet airplane should fly high where the speed for best fuel economy is the same as long-range cruise speed $\approx(M \times L/D)_{MAX}$. The right side of figure 12 shows that the optimum flight profile is to cruise climb at long-range cruise speed. However, current ATC rules require constant altitude cruise with 1219-m (4000-ft) steps. The technique chosen for the sensitivity studies to save fuel, also shown in figure 12, was to fly at long-range cruise [constant Mach at $(M \times L/D)_{MAX}$] at constant altitude within 610 m (2000 ft) of optimum using a 1219-m (4000-ft) step at long range. This causes a block fuel penalty of about 2% compared to the optimum cruise-climb procedure. A 610-m (2000-ft) step, if possible, would reduce this penalty to about 1%.

The detailed mission analysis conducted on the TAC airplane had a representative payload load factor of 55%. Increasing the payload load factor has a large impact on fuel usage per passenger kilometer (nautical mile). The 196-passenger airplane at the design range of 5556 km (3000 nmi) has changes in fuel usage relative to a 55% payload load factor as follows:

40% PL = -26% degradation
55% PL = 0% base point
60% PL = + 8% improvement
80% PL = +40% improvement
100% PL = +70% improvement

If the 5556-km (3000-nmi) mission were accomplished in three 1852-km (1000-nmi) segments with refueling at each stop, the fuel usage would increase 6%. The fuel penalties associated with the climb and acceleration phase of the mission more than offset the reduced average cruise-weight effects. Performing the mission with stops every 1852 km (1000 nmi) and not refueling at each stop would increase fuel usage by 19%.

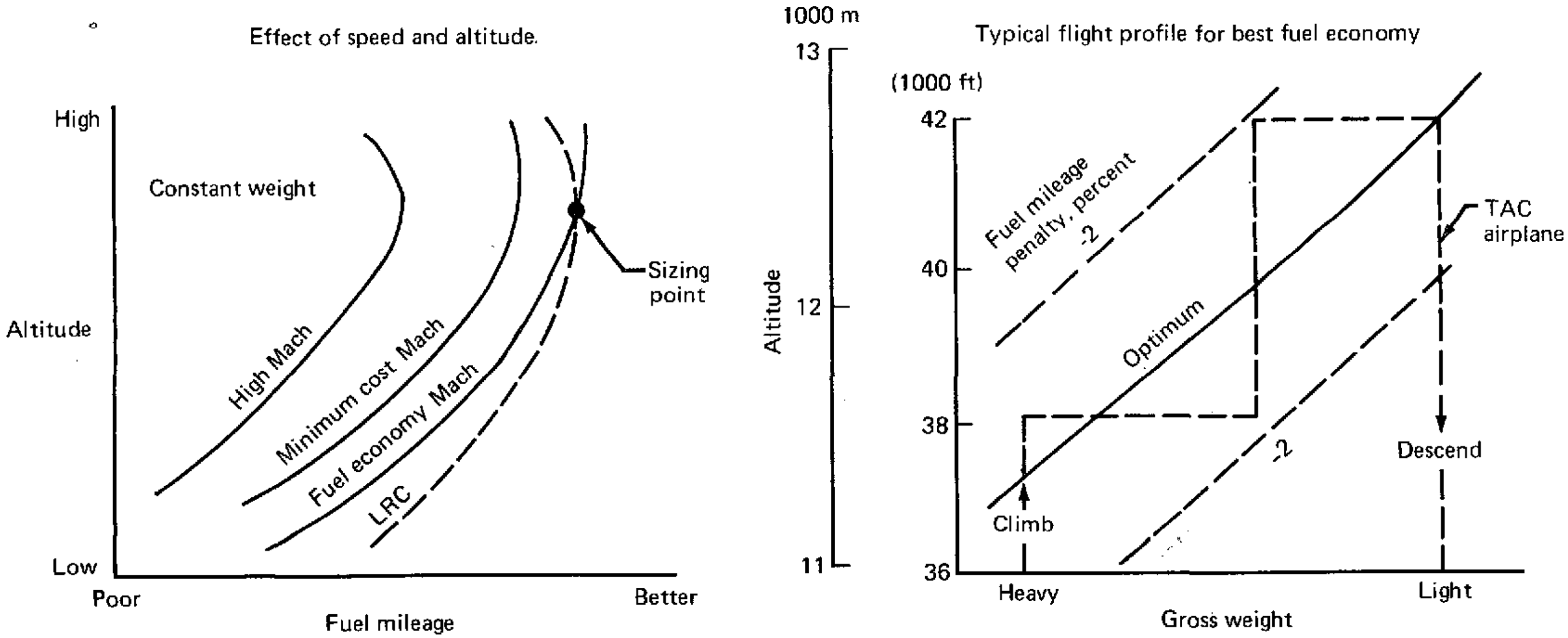


Figure 12.—Typical Operational Techniques—Cruise

It should be noted that the reserve fuel requirement is not a function of stage length but mission landing weight (i.e., OEW + payload) in determining items 9 through 14 in figure 9.

4.2.1 INTERACTION WITH AIR TRAFFIC CONTROL (ATC)

Reduced airplane speed is one parameter change considered for decreased energy consumption. Mixing of lower speed airplanes with the existing fleet can cause problems in two areas:

1. Speed variations cause additional ATC work by forcing the ATC system to resolve potential separation violations occurring when a faster airplane is overtaking a slower airplane on the same track.

2. The resolution of these conflicts requires the changing of the flightpaths of some airplanes. This results in the partial loss of the fleet fuel saving obtained by the lower speeds.

To determine the trend of these effects, an existing simulation model developed under contractor-sponsored IR&D was used. The model represents the U.S. route system into the Chicago area from the east and south, a region of heavy traffic and potential conflict. The busiest hour of traffic was used to supply representative airplane mixes and schedules. Traffic levels equal to current and two and three times current levels were studied. Airplane mixes studied included the current and replacement of 36% of the current by low-energy airplanes of M = 0.8, 0.7, and 0.6 (see fig. 13). For study purposes, the fuel consumptions of the Mach 0.8, 0.7, and 0.6 airplanes were arbitrarily assumed to have the ratios 1.00:0.95:0.90. It was also assumed that conflicts are resolved by altitude changes to less optimum flight levels where suitable altitudes are available and otherwise by holding.

For the current traffic level, the ATC workload was found to be small, and the fuel penalties at all speeds were small enough that they did not appreciably affect the assumed fuel economy effects. At twice the current traffic, ATC workload was tolerable, and fuel savings were realized for the Mach 0.8 and 0.7 airplanes. For the Mach 0.6 airplane, the workload increase was significant, and the fuel penalty for conflict resolution more than outweighed the assumed fuel savings. At three times the current traffic, ATC workload was high for all speed mixes, and the conflict resolution fuel penalties more than outweighed fuel savings for the Mach 0.8 and 0.7 airplanes and were very large for the Mach 0.6 airplane.

Exact relationships between airplane speed, ATC workload, and conflict resolution fuel penalties will depend on actual airplane mixes, penalties for off-altitude flight, traffic level, availability of parallel routes, and ATC system characteristics. However, the study results indicated that as traffic level increases, the need for ATC conflict resolution will increasingly penalize the total fleet fuel consumption due to inclusion of the slower airplanes.

Another operational technique for reducing fuel consumption is the climbing cruise in which the airplane is flown at its instantaneous optimum altitude throughout cruise, climbing slowly as fuel weight decreases. Present ATC practice on most routes is to fly at a single altitude throughout cruise on the busiest routes and to make a single-step change, typically 1219 m (4000 ft), where lighter traffic permits.

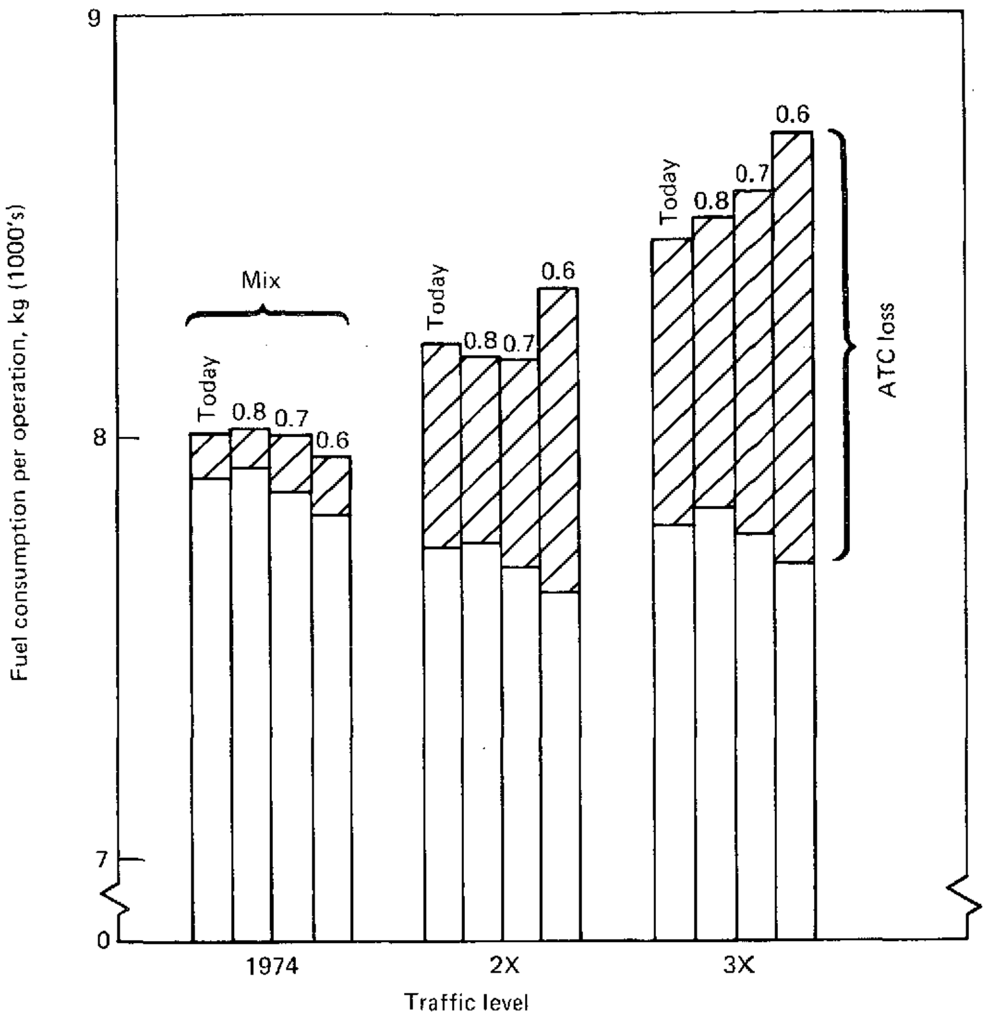


Figure 13.—Fuel Consumption Versus Traffic Level and Speed Mix

The 1219-m (4000-ft) minimum altitude increment is necessary because the high altitude flight levels are at 610-m (2000-ft) altitude increments for safe altitude separation with alternate flight levels reserved for each direction of traffic. A decrease in the flight level separation from 610 m (2000 ft) to 305 m (1000 ft) is currently under consideration. When this change is made, cruise profiles with 610-m (2000-ft) step altitude changes will be possible on many routes.

In addition, there are now some airways that are designated as one way with traffic in the same direction at all flight levels. On these routes, 610-m (2000-ft) step altitude changes are now possible, and 305-m (1000-ft) increments will be possible on many routes.

On many of the long-haul routes, especially in the western two-thirds of the United States, traffic is sparse enough that it is possible to develop safe procedures for continuous climbing-cruise profiles. With increasing experience, increasing numbers of one-way airways, greater ATC automation, and improved navigation and surveillance, extension of climbing-cruise operation to an appreciable fraction of the total operations should be possible.

4.3 WING GEOMETRY–CRUISE SPEED STUDIES

The principal objective of this study was to determine the effect of wing geometry and cruise Mach number on fuel consumption, noise, and economics. Variations in wing geometry were analytically considered to determine the sensitivities and tradeoffs among structural weight, aerodynamic efficiencies, and cruise Mach number, and the resultant effect on fuel consumption, noise, and economics. Studies were conducted for a selected flight profile, for mission rules, and for operational procedures discussed in section 4.1.

As a result of this study, an optimum wing geometry and cruise Mach number were selected for incorporation into a configuration to minimize fuel consumption.

4.3.1 GENERAL APPROACH

A general study approach was adopted that provided for the selection of a configuration data base in the study area of interest and an analysis procedure that would support a high degree of confidence in the trend results. The basic study was developed in two parts.

1. The impact on the wing weight due to variations in wing geometry and cruise Mach number

2. The impact on the airplane weight, fuel usage, economics, and noise due to variations in wing geometry and cruise Mach number while maintaining constant payload/range performance

This step approach was necessary to separately develop and understand the effect of each change in design parameters on the wing and on the integrated airplane. As the study progressed, the effect of geometry and speed changes on a current aluminum technology wing and airplane was determined. The effect of incorporating advanced technology was also examined to retain cognizance of the potential impact on study results at very high wing aspect ratios. Figure 14 depicts this analysis approach, which provided for comparison of study results at intermediate steps in the overall process.

4.3.2 WING ANALYSIS

4.3.2.1 Wing Analysis Approach

The initial selection of the wing was made from recent contractor-independent wing-geometry investigations in the study area of interest and on which extensive aeroelastic, flutter and fatigue analyses had been accomplished. Although the selected wing area was somewhat larger than that required for the TAC/Energy airplane, the details available and extensive work accomplished benefited this study through a reduction of time associated with the selection of basic wing geometry parameters and aeroelastic analysis computer-run checkouts, as well as providing high confidence results.

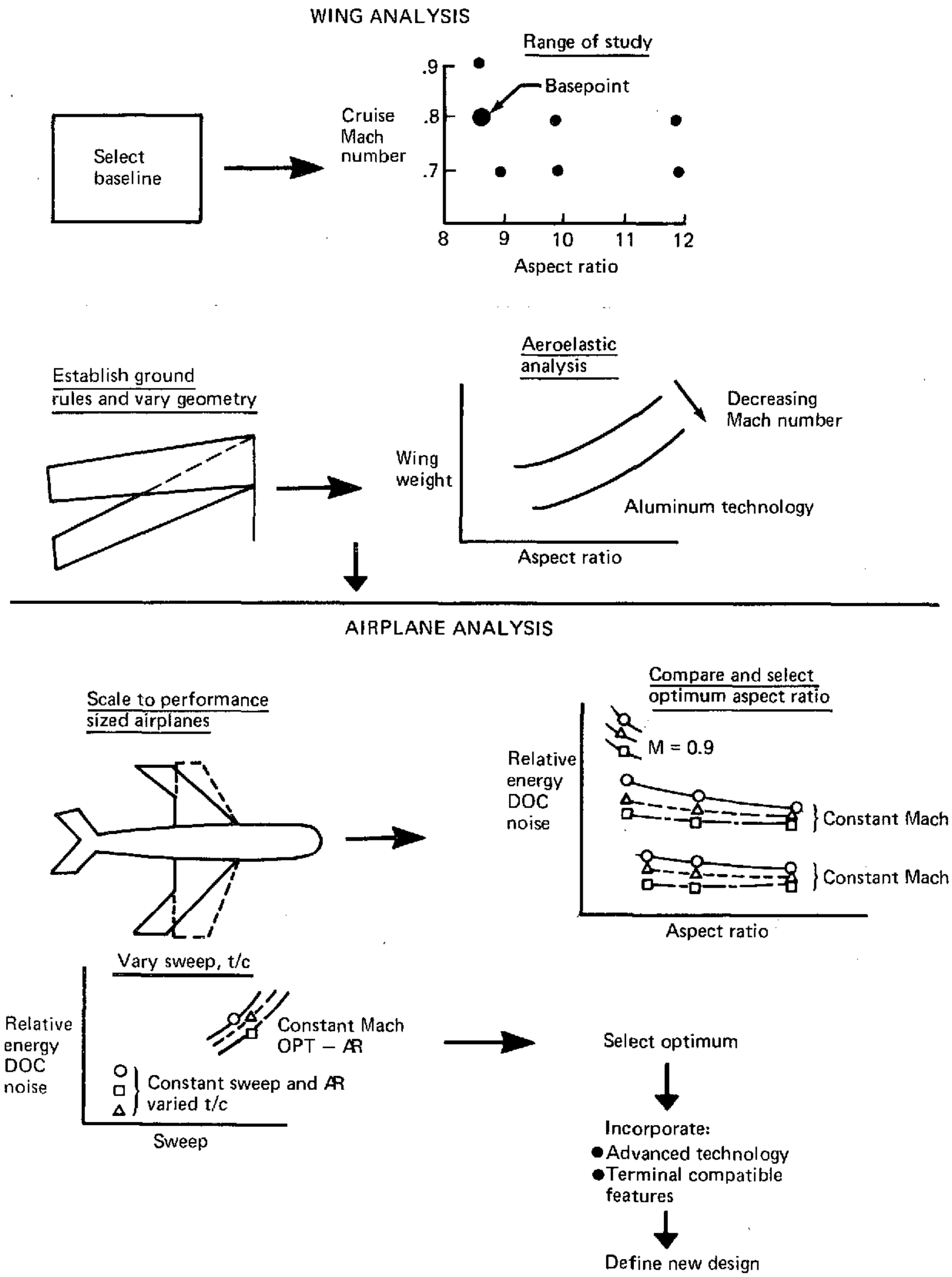


Figure 14.—Wing Geometry Study Approach

Aspect ratio and Mach number design points to be investigated for effects on the wing were selected at lower speeds and higher aspect ratios than the basic TAC, Mach 0.9, AR 9.0 airplane in anticipation of the final fuel consumption and airplane sizing trends. The TAC airplane Mach 0.9 wing with current aluminum structure was analyzed in the airplane analysis cycle by scaling from the Mach 0.8 performance-sized wing.

Study rules were established concerning the basic wing/airplane interface and structural arrangement on the modified TAC configuration. TAC wing design features (i.e., tip vortex control features, and advanced composites) were eliminated to ensure the capability to measure the effect of wing geometry variations without these effects being impacted by advanced technology or terminal compatible features. While wing-mounted engine locations were held constant in percent of span, aerodynamic AR was varied for each Mach number. At a constant trapezoidal wing area, detailed wing aeroelastic, flutter, and fatigue analyses were conducted. The analyses resulted in the definition of total wing structural weight, including fixed and movable leading and trailing edges at each aspect ratio. Figure 15 shows the planform rules and structural arrangement scheme that were maintained throughout the study. Table 5 identifies the relevant, critical, wing-design parameters selected for the study. Throughout the aeroelastic analysis, the following parameters were held constant.

- Trapezoidal wing area
- Airplane gross weight
- Trapezoidal spanwise thickness distribution
- Placard speed
- Engine weight and location (fig. 15)
- Fuel tank locations (as percent of semispan)
- Tail arm (distance between quarter-chord wing and quarter-chord horizontal tail)
- Body diameter (same as TAC airplane) [5.25 m (206.5 in.)]
- C.G. range (in meters) for loadability
- Control surfaces definition (fig. 15)

A 167-m/s (325-kn) placard speed was originally selected for this study because it was felt that this lower placard speed would result in a lower wing weight and consequently improved fuel economy. However, because current aircraft have a higher placard speed, a study was conducted at 193 m/s (375 kn) on Mach 0.8 wings to evaluate effects on wing weight with increased aspect ratio. Results are shown in section 4.3.2.3.

Wing aeroelastic analysis for each planform encompassed generation of airloads and completion of a structural sizing cycle, using the selected spanwise trapezoidal-thickness distribution and cruise span-load distribution. Approximately 30 design conditions were

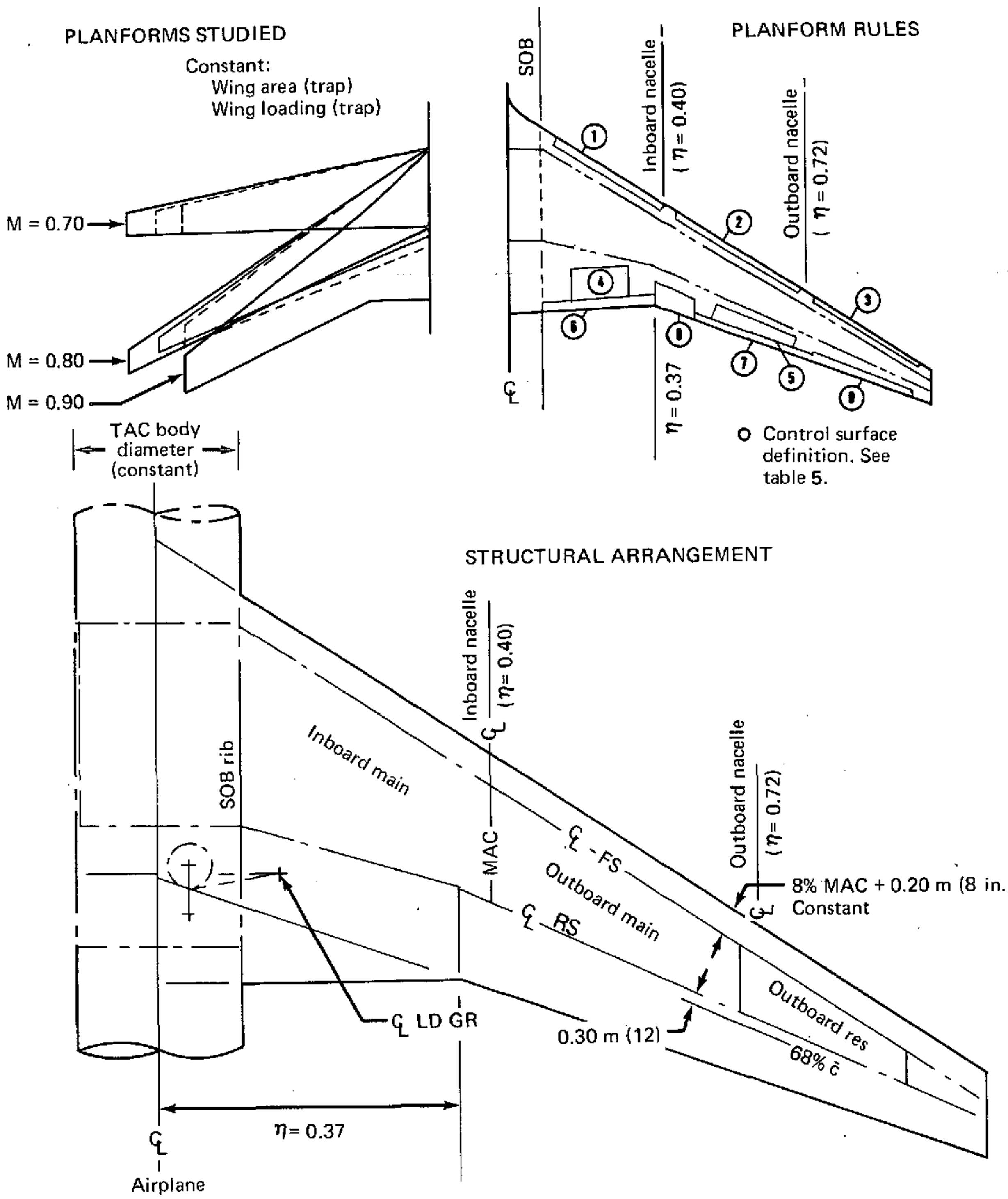


Figure 15.—Planform Rules and Structural Arrangement

Table 5.—Wing Design Parameters and Control Surface Definition

Item	Mach 0.815	Mach 0.7
Airplane gross wt	191 420 kg (422 000 lb)	191 420 kg (422 000 lb)
AR studied	8.6, 10, 12	9, 10, 12
Airfoil	Advanced	Advanced
Trapezoidal area	297 m^2 (3 200 ft^2)	297 m^2 (3 200 ft^2)
Taper ratio	0.25	0.30
Quarter chord sweep	30°	10°
Thickness ratio at SOB	0.155	0.19
Thickness ratio at TIP	0.100	0.170

CONTROL SURFACE DEFINITION (Refer to fig. 15.)

1. Fixed camber leading-edge flap
2. Variable camber leading-edge flap—inboard
3. Variable camber leading-edge flap—outboard
4. Trailing-edge spoiler—inboard
5. Trailing-edge spoiler—outboard
6. Trailing-edge double-slotted flap—inboard
7. Trailing-edge double-slotted flap—outboard
8. High speed aileron
9. Low speed aileron

considered. For each condition, a detailed structural analysis was performed at numerous spanwise locations. The data points, shown on the speed-altitude and V-n diagrams in figure 16 for the Mach 0.80 wing, are typical of the conditions considered for each airplane. Early in the preliminary design phase, this analysis procedure ensured that FAR 25 requirements for maneuver and gust envelopes had essentially been met and that the maximum load for each part of the wing structure was defined.

Wing structural design loads were calculated in recognition of the advanced technology wing airfoil geometry, including wing-root tailoring with maximum thickness sweeping forward near the body suitable for the Mach number study (selected critical Mach number). After completion of the sizing cycle, flutter and fatigue evaluations were made of each planform. Figure 17 presents the general approach, using results of the wing aeroelastic analysis. Also shown in figure 17 is the procedure followed in the development leading to the analysis of airplanes sized to constant range and payload.

4.3.2.2 Wing Analysis Methods

Wing aeroelastic analysis involved the use of a contractor-developed digital computer program that provides integrated wing structural design capability for subsonic high AR configurations. It was thus possible to conduct iterative wing aeroelastic analysis and obtain design loads, structural sizing, stiffness properties, and weight estimates. This iterative process was required because of the interaction between wing elasticity and design loads.

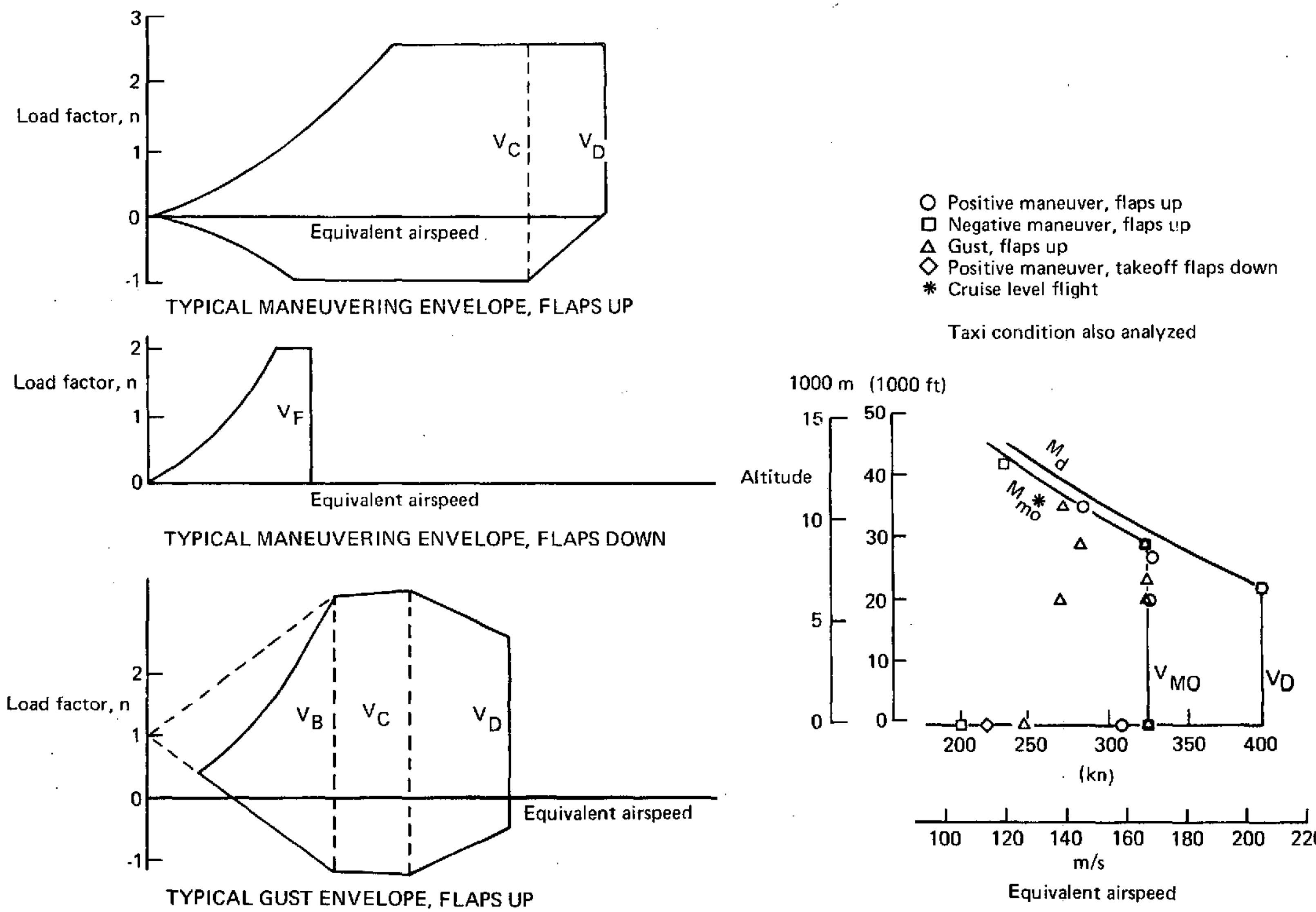


Figure 16.—Wing Structural Design Conditions

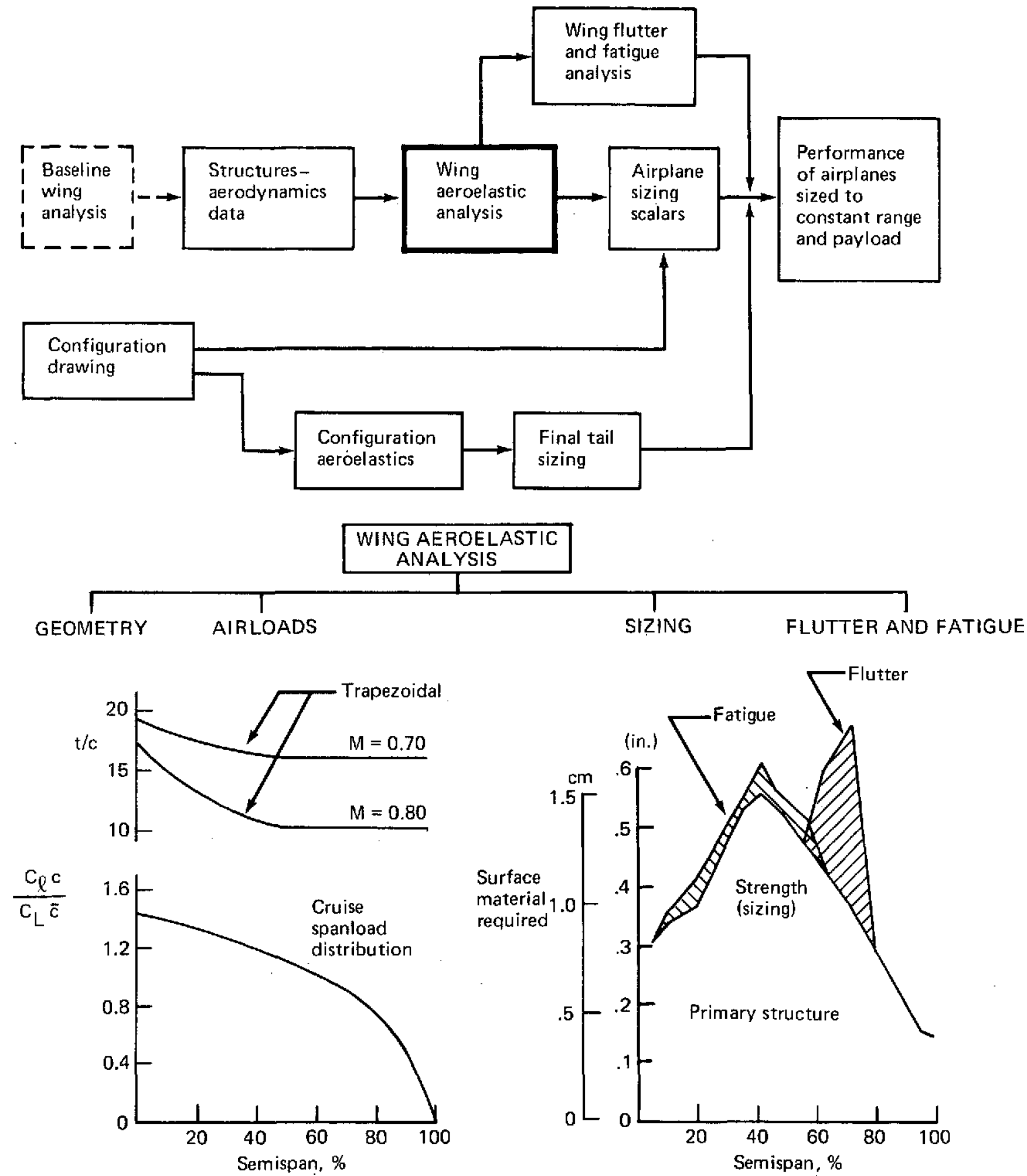


Figure 17.—Approach, Wing Aeroelastic Analysis

A flow chart showing general data flow, major program operations, and various modules is shown in figure 18. This analysis can be performed either with a minimal data input using typical preliminary design assumptions or with final design data if available. The analysis encompasses lifting line theory, linear beam theory, weight analysis of the idealized primary box structure, and statistical analysis of nonoptimum and secondary structure. All wings analyzed were of aluminum skin-stringer construction with a 7075-T651 upper surface and 2024-T351 lower surface skin.

Mass and stiffness data from these analyses were used directly in a wing flutter analysis. In addition to aspect ratio, variations in strut stiffness and the spanwise location of the outboard nacelle were considered. A reasonable amount of strut tuning was used. In the case where the flutter speed was deficient (AR = 12.0), a wing-stiffening scheme was evolved to achieve flutter clearance and assess weight penalties. The airplane size scaling process was modified to account for the flutter penalties.

Each wing was analyzed for fatigue life to ensure the equivalent of 20 years of service life. Fatigue margins were checked using contractor-developed procedures. The cross-sectional areas of surface material required to prevent negative values of fatigue margins were calculated and converted to weight.

From these wing analysis results, selection of an optimum airplane configuration involved a two-step approach:

1. Aspect ratio was varied while keeping all other parameters constant. This was done at both M = 0.8 and 0.7. An optimum AR was selected based on fuel usage, economics, and noise, using AR study results in conjunction with an airplane configuration. Figure 19 shows this process. (Wing AR study results are discussed in sec. 4.3.2.3 and shown in fig. 23.)

2. Aspect ratio selected from item 1 was used as a baseline for wing-sweep and thickness ratio trades. Around the Mach 0.8 wing it was possible to vary both sweep and thickness and compare wing geometry efficiencies. Mach number increases and thickness decreases at constant sweep were considered for the Mach 0.7 wings because of practical limitations in achieving wing sweeps less than 10° or thicknesses greater than 19% of the chord at the side of the body. Data points evaluated in the sweep-thickness trades are shown in figure 20.

Data points 3 and 4 around the Mach 0.7 baseline are the result of using parametric/statistical wing-weight analysis methods rather than an aeroelastic solution. This resulted in some decrease in confidence in the wing-weight analysis at points 3 and 4 as compared to the Mach 0.7 baseline; however, the weight trends are as expected and are consistent with the results at M = 0.8 showing increasing weight with decreasing wing thickness. (Refer to fig. 26.)

The statistical/parametric method for M = 0.7 was preferred over a straight thickness correction because it considered the effects of interdependent parameters that would have otherwise been ignored.

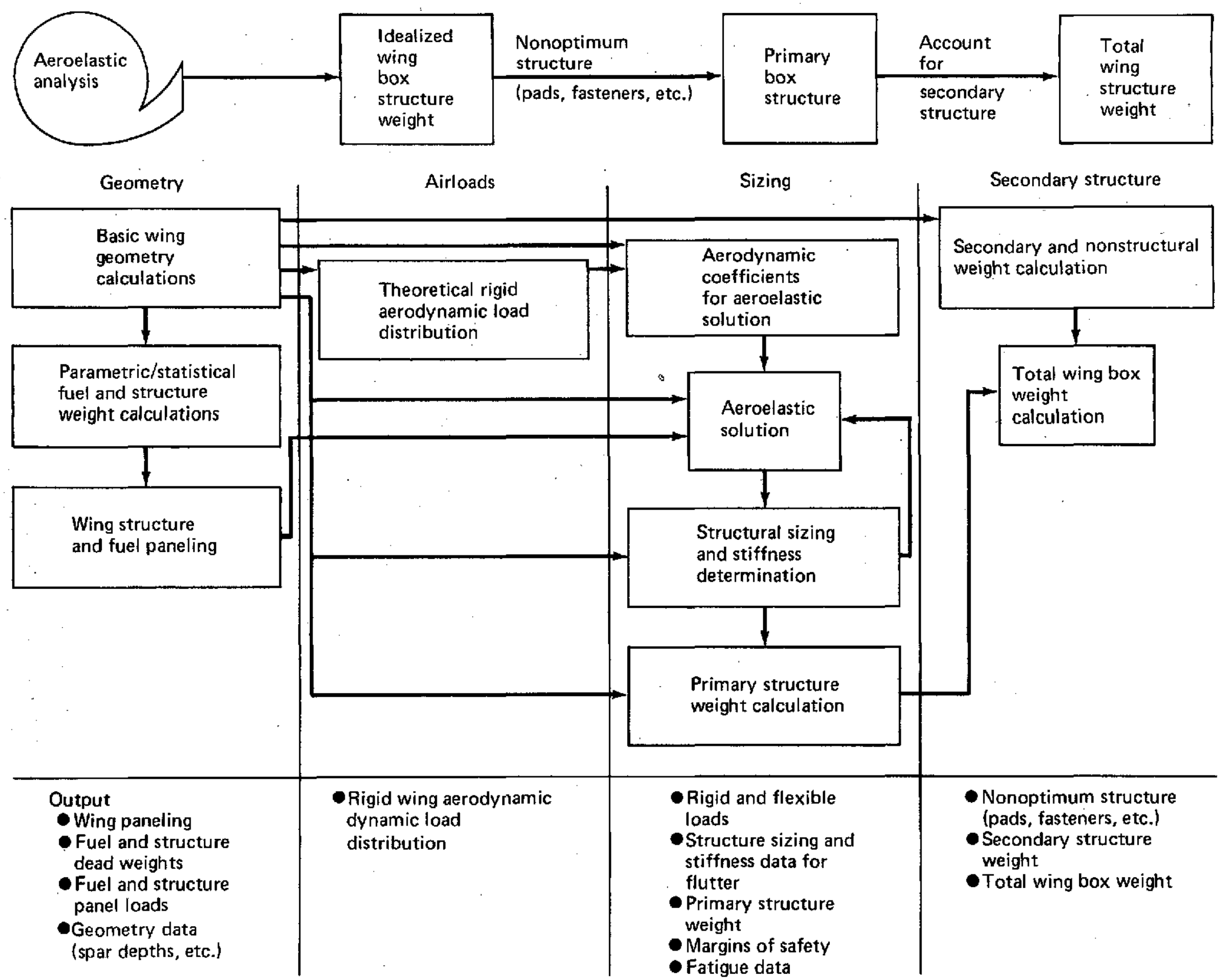


Figure 18.—Results Application, Wing Aeroelastic Analysis

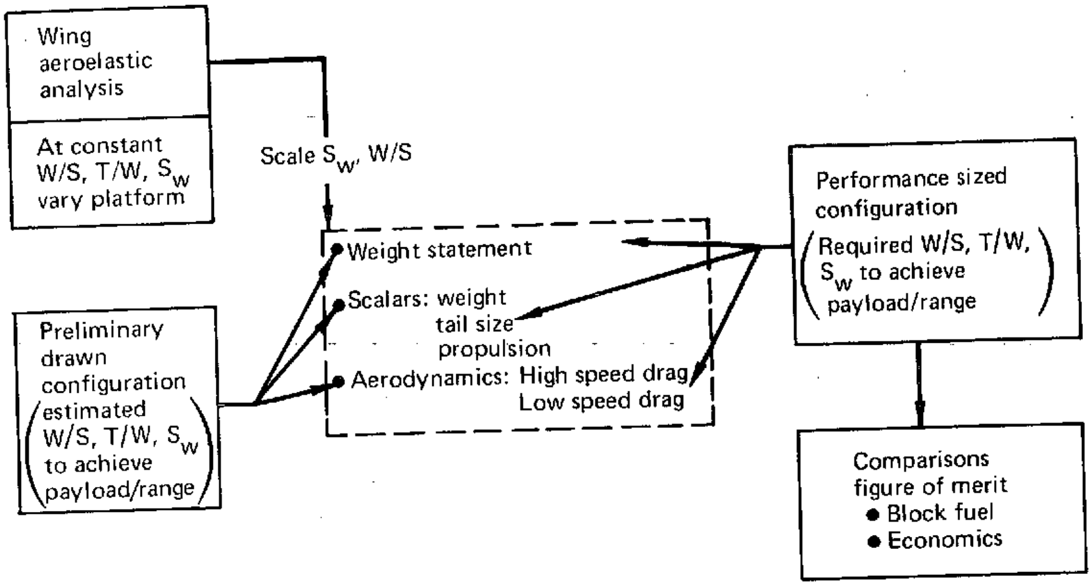


Figure 19.—Wing Planform Study, Data Development

4.3.2.3 Wing Analysis Results

The wing structural analysis results were expressed as a function of aerodynamic aspect ratio. (Refer to fig. 23 for designs at M = 0.7 and 0.8.) Data for wing design refinement at the selected AR is expressed as a function of wing quarter-chord sweep with trends shown for thickness ratio and Mach number perturbations.

The wing geometry and load parameters illustrated in figure 21 provide insight into the wing weight variations with AR and Mach number. The variation in wing gross planform area with aspect ratio is due to the trailing-edge extensions necessary for proper incorporation of the airplane main landing gear. The more highly swept Mach 0.8 wing is influenced by main landing gear integration to a greater degree than the Mach 0.7 wing. Because gross wing area varies in this manner, wing loading also varies slightly with changes in AR with the Mach 0.7 wing having a higher wing loading than the Mach 0.8 wing. Because of the difference in sweep angle of the Mach 0.7 and 0.8 wings, the lift curve slope is greater for the Mach 0.7 wing, resulting in higher gust load factors for the Mach 0.7 wing. As shown in figure 22, the ultimate side-of-body bending moments are dominated by gust loads for the Mach 0.7 wing and by maneuver loads for the Mach 0.8 wing.

This does not imply that the wing is gust critical at every spanwise analysis station since the sizing process involves interaction equations considering shear, moment, and torsion for the design load condition. However, the Mach 0.7 wing has greater structural box depth than the Mach 0.8 wing, resulting in typically lower ultimate end loads for the Mach 0.7 wing primary structural box. The preceding described relationships logically result in the idealized wing structural box weight trends shown in figure 22. The wing secondary structure weight trends were found to be dominated by the relative ease of landing gear integration in the trailing edge with the Mach 0.8 wing suffering a greater penalty to trailing-edge structure

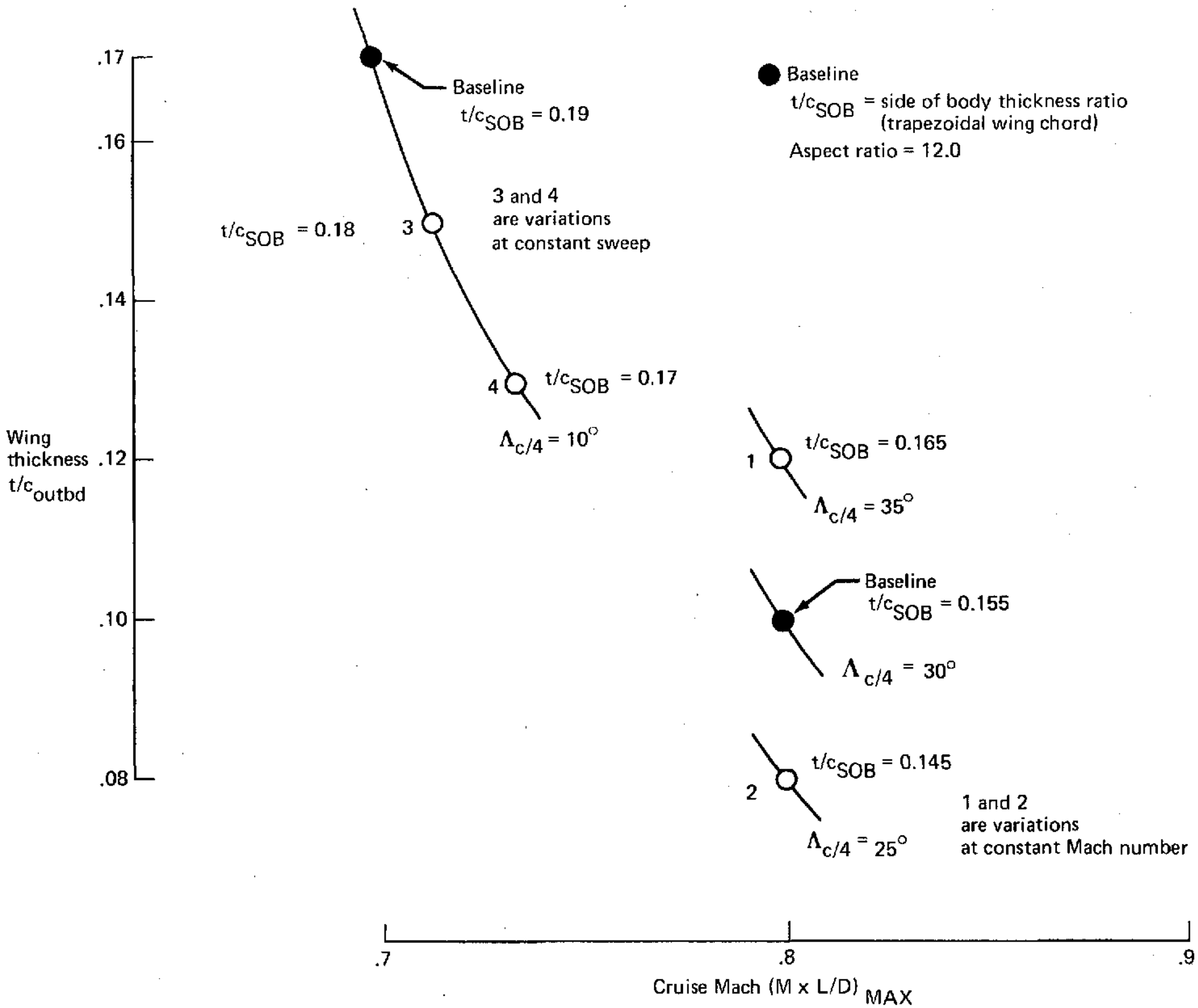
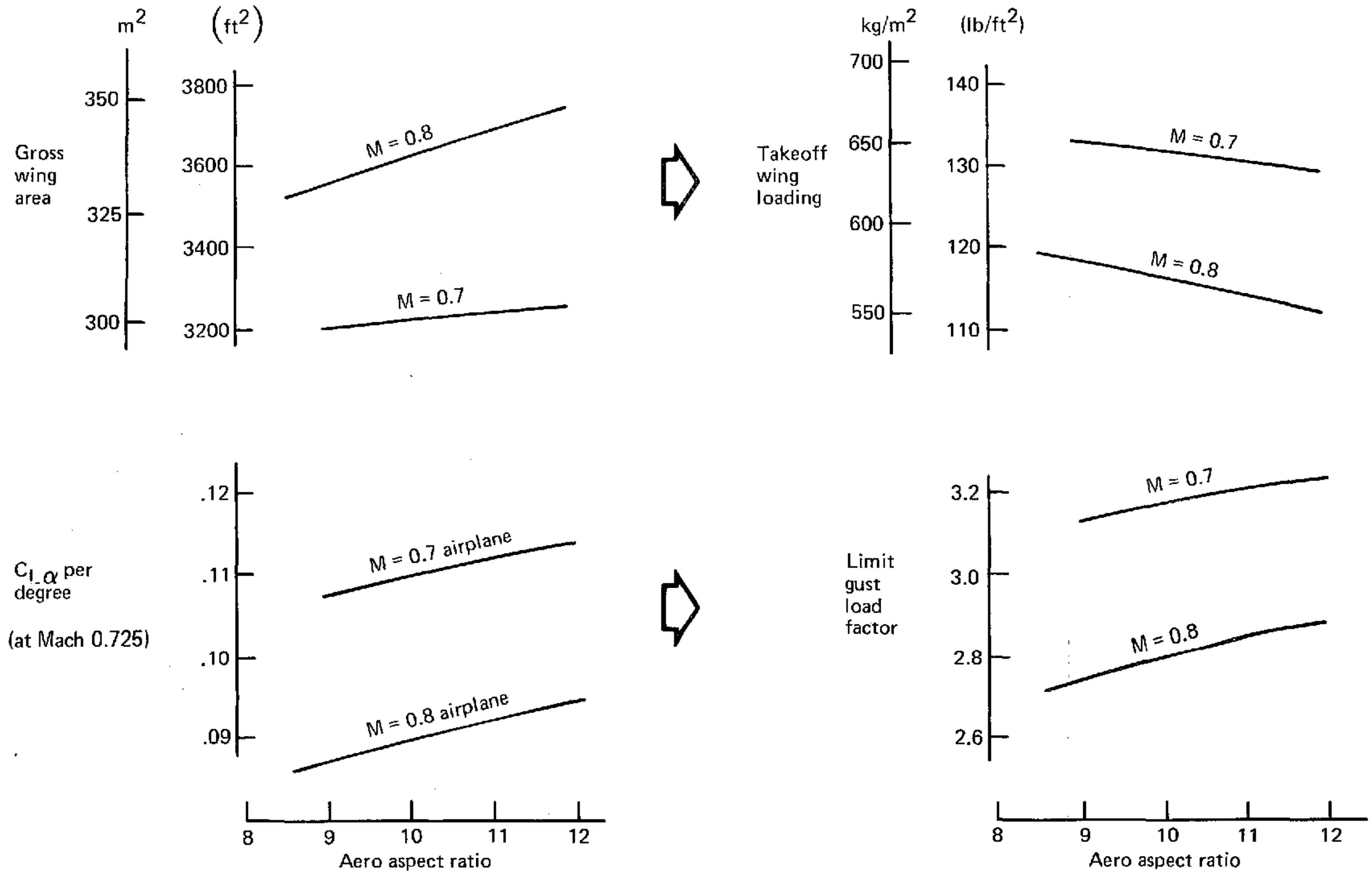
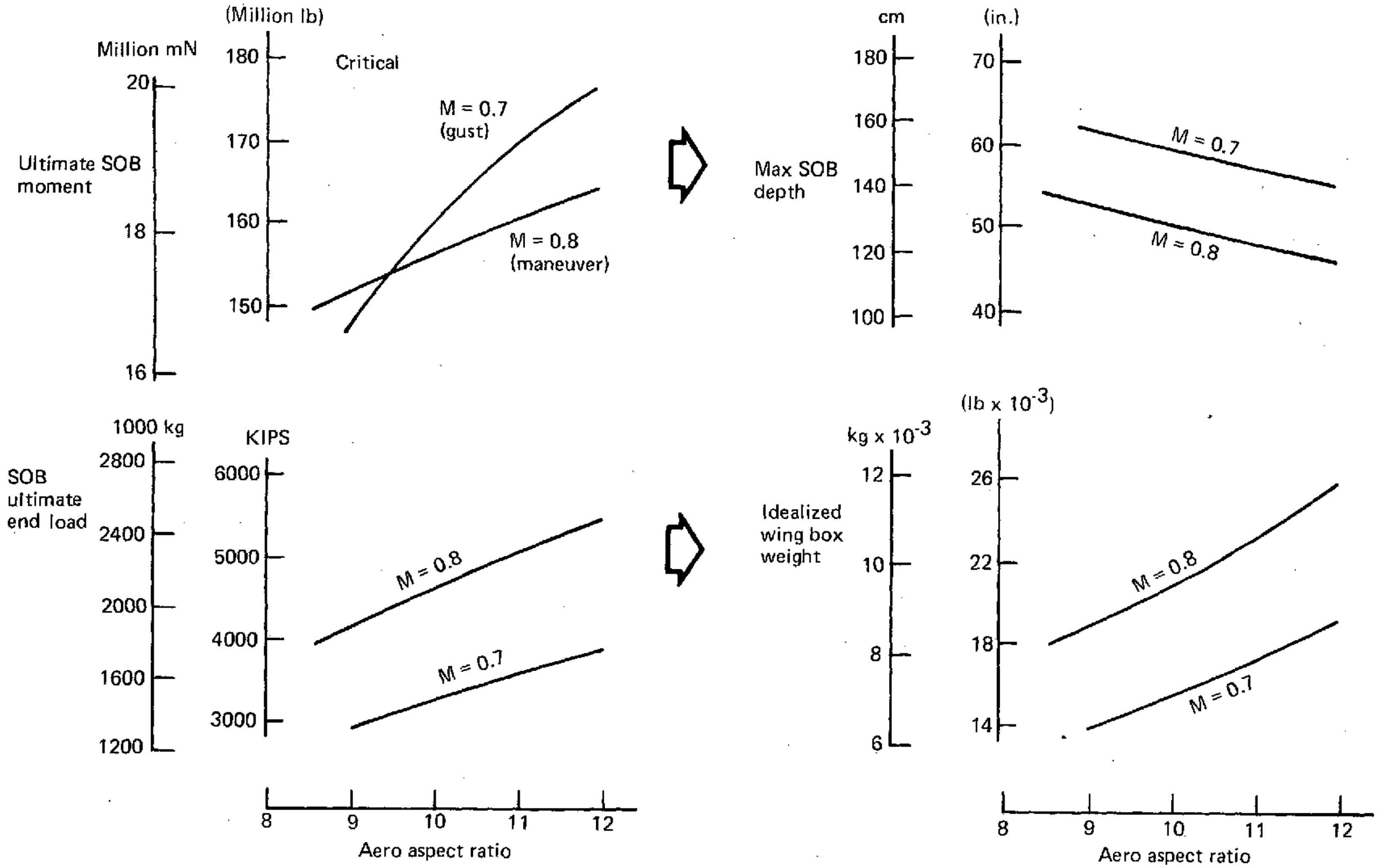


Figure 20.—Wing Sweep and Thickness Study



Constant: TOGW and S_W (trapezoidal)

Figure 21.—Takeoff Wing Loading and Limit Gust Load, Wing Aeroelastic Analysis



Constant: TOGW and S_w (trapezoidal)

Figure 22.—Wing Box Weight and SOB Depth, Wing Aeroelastic Analysis

and a somewhat greater sensitivity to changing AR than the Mach 0.7 wing. The combined effects of these trends are shown in the plot of total wing weight versus aerodynamic AR and Mach number in figure 23. The advanced technology structural concepts defined during the ATT studies (ref. 1) were applied to the Mach 0.8 wing designs, and weight trends with aspect ratio were found to be similar with the exception of wings near AR 12 where the effects of flutter and fatigue were less significant for advanced technology structure. The lower cross-hatched band in figure 23 indicates the magnitude of reduction in OEW at M = 0.8 that could be expected if composite structure was used instead of aluminum. The upper and lower boundaries of the band reflect a 10% and 25% wing structural weight reduction, respectively. At the higher AR's (12), most of the OEW penalty for flutter is removed, indicating that the use of advanced technology wing structure will be an important consideration in wing design.

The selection of placard speed was previously discussed in section 4.3.2.1. The effect on wing weight of increasing the placard speed from 167 m/s (325 KEAS) to 193 m/s (375 KEAS), as shown in figure 24 for the strength designed wing, is fairly constant over the entire range of AR's studied. However, the wings at the 193-m/s (375-KEAS) placard speed show flutter encounter at a lower AR compared to wings at the 167-m/s 325-KEAS) placard speed selected for this study.

The wing weights for the preceding described aspect ratio and Mach number variations were incorporated with proper scaling in airplane configurations as discussed in section 4.3.3. These were performance sized to a constant payload/range mission in order to allow rigorous evaluation and comparison. Figure 25 is a plot of the performance-sized operating empty weights (OEW) versus AR and Mach number. The Mach 0.9 data are based on analysis at the AR 8.6 data point. The OEW trend line for M = 0.9 at higher AR's is speculative and is based on study results at M = 0.8 and 0.7. Similarly, the OEW trend lines for M = 0.7 and 0.8 beyond AR 12 are speculative. The trend lines are extended beyond the actual study limits to illustrate a possible aspect ratio at which the Mach 0.7 wing would encounter flutter and fatigue penalties. Figure 25 shows the same band of wing structural weight as indicated in figure 23.

At completion of the aspect ratio-Mach number study, further refinement of wing design was accomplished by studying small perturbations of sweep and thickness on the AR 12 wings at M = 0.8 and 0.7 as described by figure 20. Because the baseline Mach 0.7 wing is already at maximum practical thickness and unswept to only 10°, the reductions in thickness were studied at appropriately increased cruise Mach numbers. For the Mach 0.8 wing, thickness and sweep were varied appropriately to maintain constant cruise Mach number. Figure 26 shows the resulting wing weights and the performance-sized OEW's. These results indicate that, although wing weight is decreasing with increase in thickness ratio for a constant wing area and gross weight, the net airplane effect for constant range and payload may be an increase in OEW.

4.3.3 AIRPLANE ANALYSIS

4.3.3.1 Airplane Analysis Approach

Determination of the effect of change in aspect ratio on airplanes sized to a constant payload/range was achieved through the development and application of scaling rules. Wing

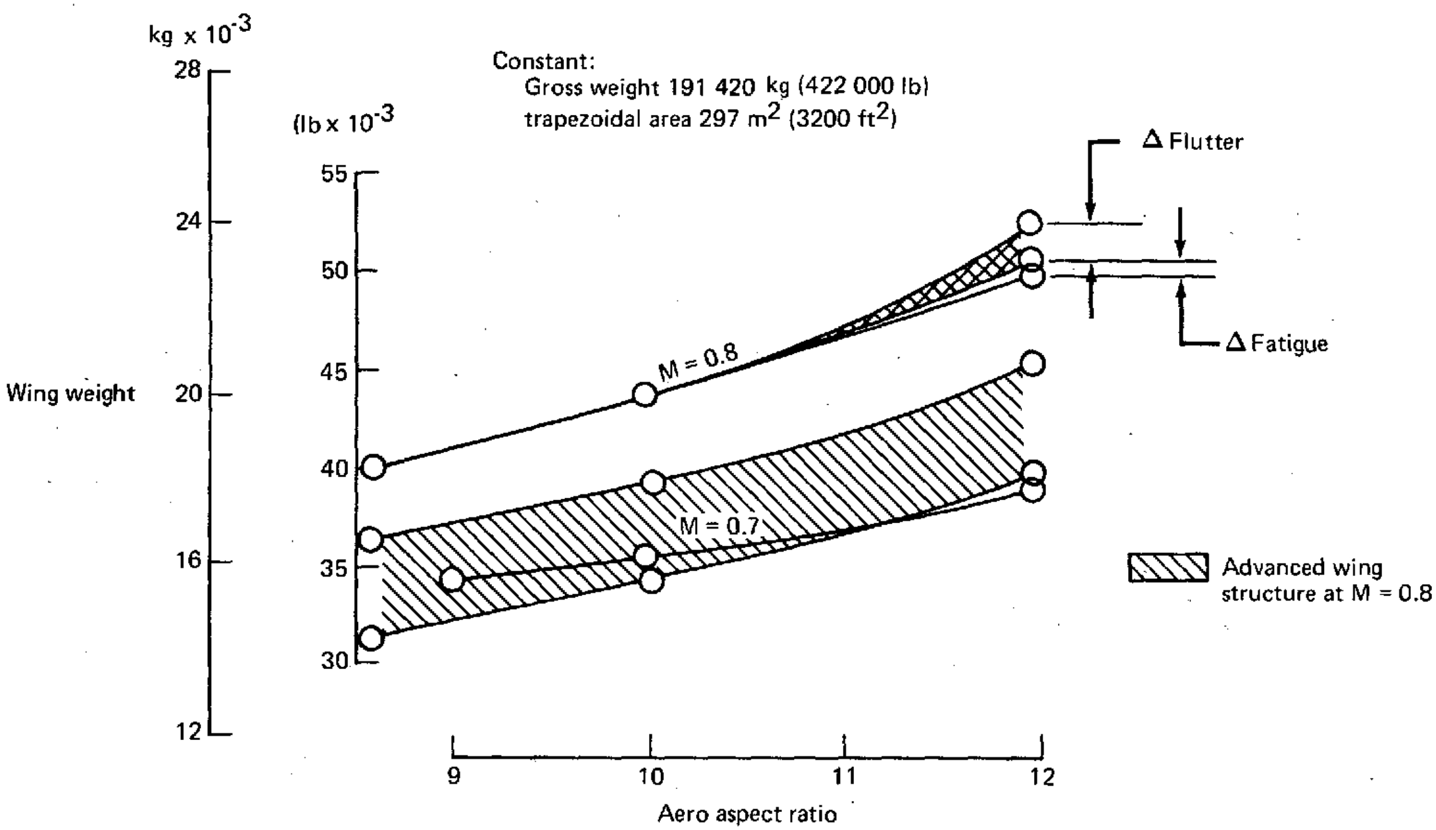


Figure 23.—Wing Weight Versus Aspect Ratio, Wing Aeroelastic Analysis

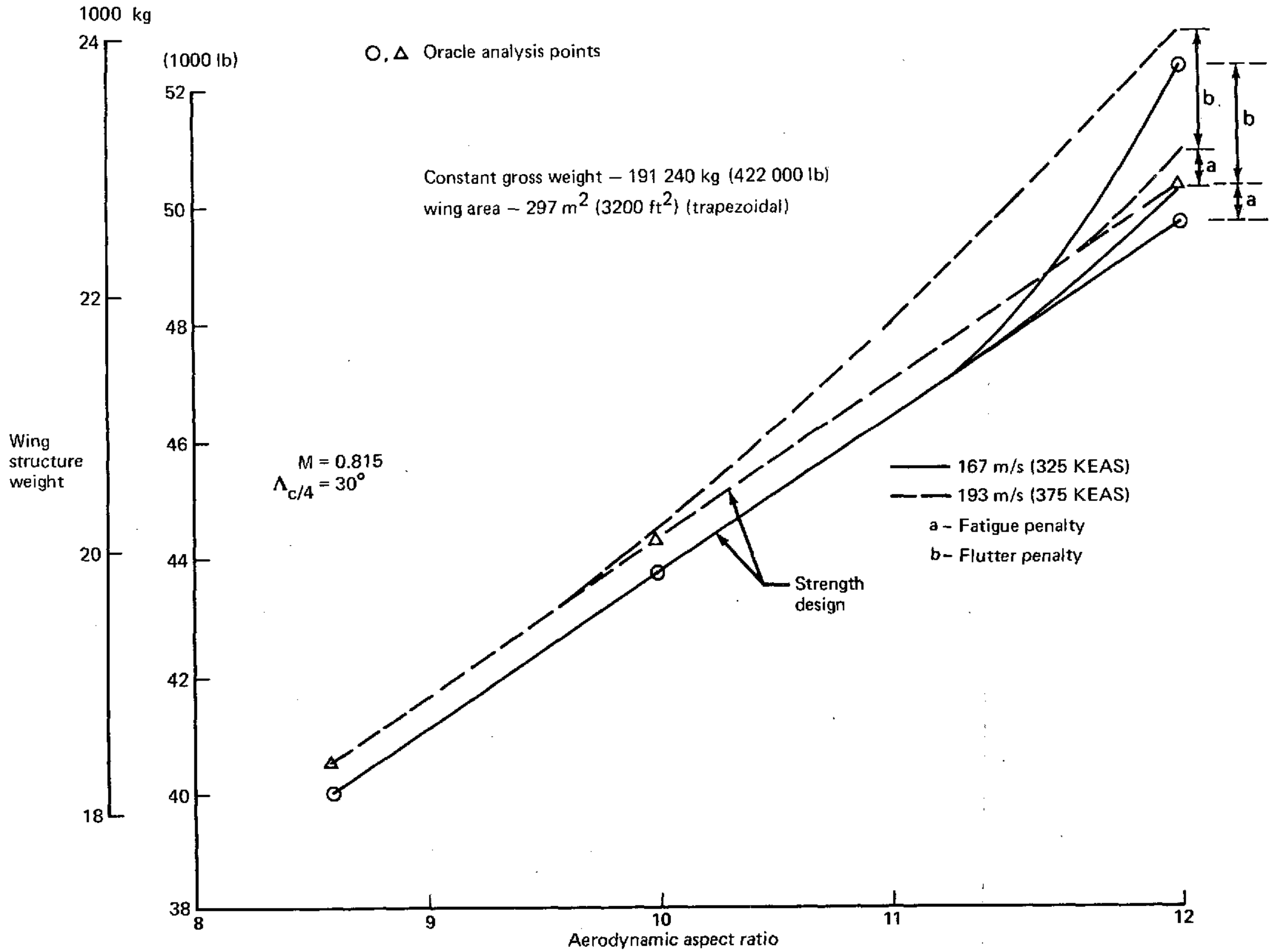


Figure 24.—Placard Speed Studies

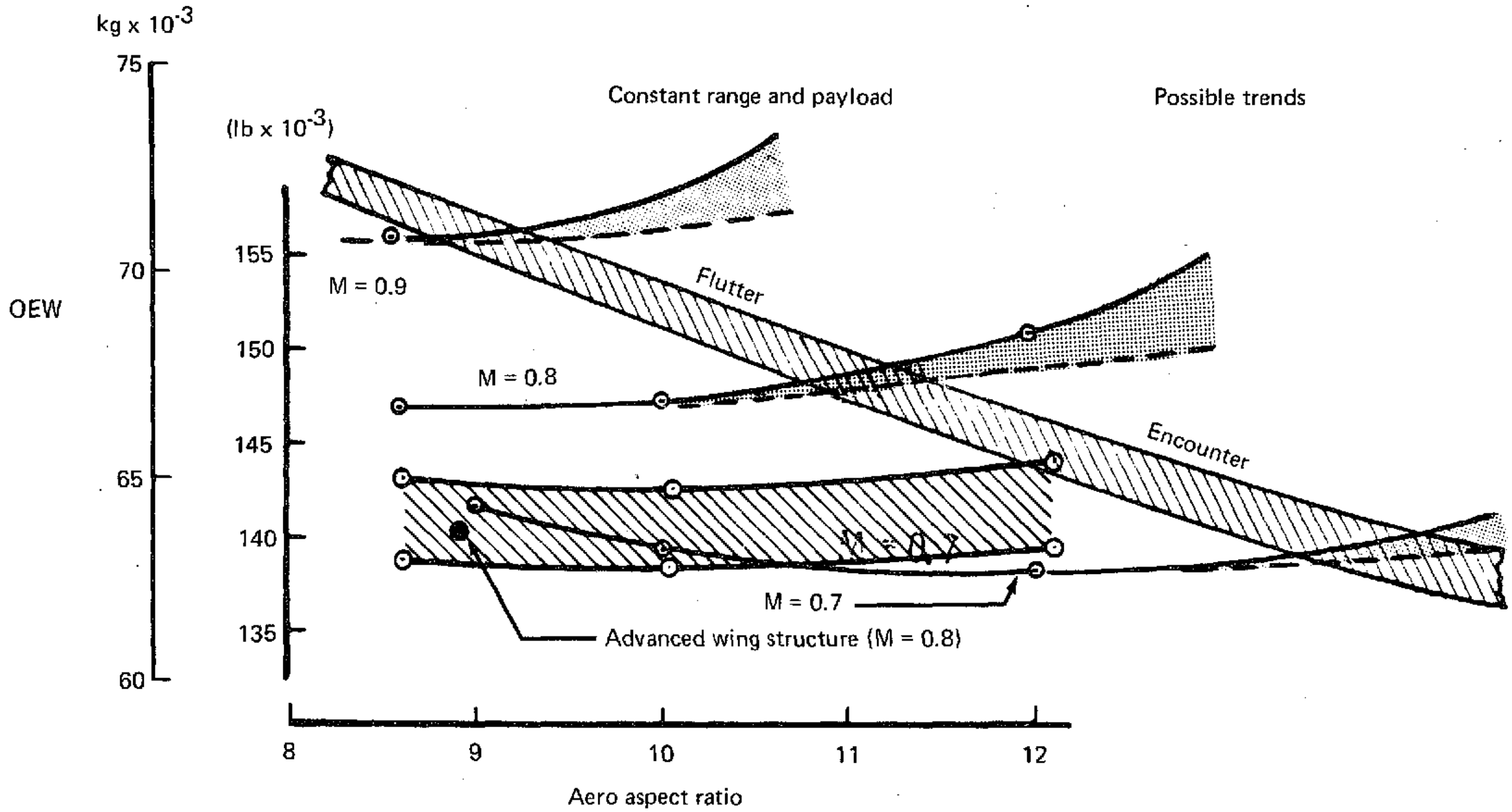


Figure 25.—OEW Versus Aspect Ratio, Wing Aeroelastic Analysis

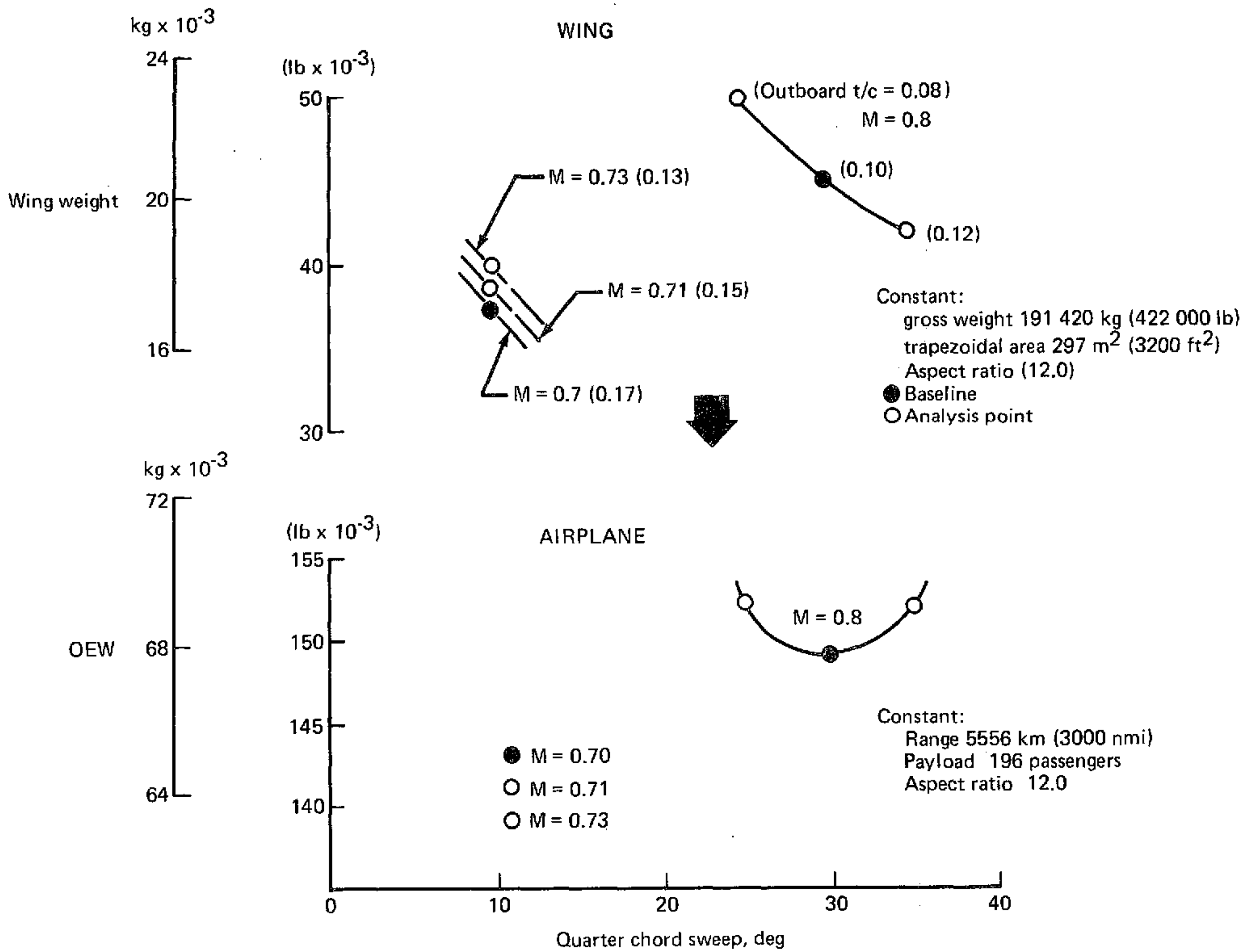


Figure 26.—Wing Weight and OEW Versus Sweep, Wing Aeroelastic Analysis

area and weight scaling, tail size scaling, engine scaling, and low- and high-speed drag scalars were applied to develop relative airplane comparisons considering fuel consumption, direct operating costs (DOC), and community noise at constant selected cruise Mach numbers. Optimum AR's were then selected and, depending on the design-speed and wing-planform combination, variations were made in sweep and wing thickness ratio or in wing thickness only. New wing weights were calculated, and new weight, drag, and stability and control scalars were utilized in developing data providing for selection of an optimum current technology low-energy airplane.

Beneficial effects of increased wing AR on both takeoff and landing and cruise performance, which will tend to offset the detrimental effects of increased weight due to aspect ratio, are illustrated in figure 27 on the Mach 0.8 wing. The substantial improvement in the lift-to-drag (L/D) ratio versus lift coefficient (C_L) envelope with increased AR is shown for takeoff and landing for best possible capability versus flap setting at the appropriate speed condition (1.2 V_S for takeoff and 1.3 V_S for landing). These improvements are available for the optimization of noise, L/D versus field length, and C_L for a particular set of design objectives and constraints. Also shown is the corresponding substantial improvement in cruise L/D with increased aspect ratio from 16.8 at AR = 8.6 to 18.2 at AR = 12 (approximately 8%). This would correspond to an improvement in fuel burned of about 8% if nothing else happened; e.g., if it were not offset by increased wing weight. It is also important to note that the optimum cruise C_L increases from 0.53 to 0.60 when AR increases from 8.6 to 12. It is obviously necessary to develop wing designs optimized for higher cruise C_L's to fully understand the trades involved in designing wings with high AR's. In this case no data were available for wings designed for cruise C_L's much greater than about 0.45; the influence of this on overall study results is discussed later.

The effects of reduced design cruise speed on both takeoff and landing and cruise performance for a fixed-wing AR are shown in figure 28. These effects must be considered in conjunction with the beneficial weight effects shown for decreased wing sweep and increased thickness that go with reduced design cruise speeds. The left side of figure 28 shows the substantial improvement with decreased wing sweep (and reduced cruise speed) in the L/D versus C_L envelope available for optimizing noise, L/D versus field length, and C_L for a particular set of design objectives and constraints. However, the right side of figure 28 shows that as design cruise speed is reduced, the combined effects of reduced sweep and increased thickness cause the L/D ratio to remain essentially constant. Also note that as cruise speed is decreased from M = 0.9 to M = 0.73, the optimum cruise C_L increases from 0.50 to about 0.58. Again, as in the case of increased wing AR, it is necessary to develop wing designs optimized for higher cruise C_L's to fully understand the trades possible with decreased cruise speed. The influence of the baseline wing design choice (C_L = 0.45) on overall study results will be discussed later. In terms of L/D, there is little change as speed is reduced; however, V/SFC is reduced. (Refer to fig. 42.) Hence, overall cruise efficiency (L/D x V/SFC) is not improved by reducing cruise Mach number. The interaction between lighter weight, improved takeoff and landing performance, and nearly constant cruise efficiency will determine the net effect on fuel usage of reduced cruise Mach number.

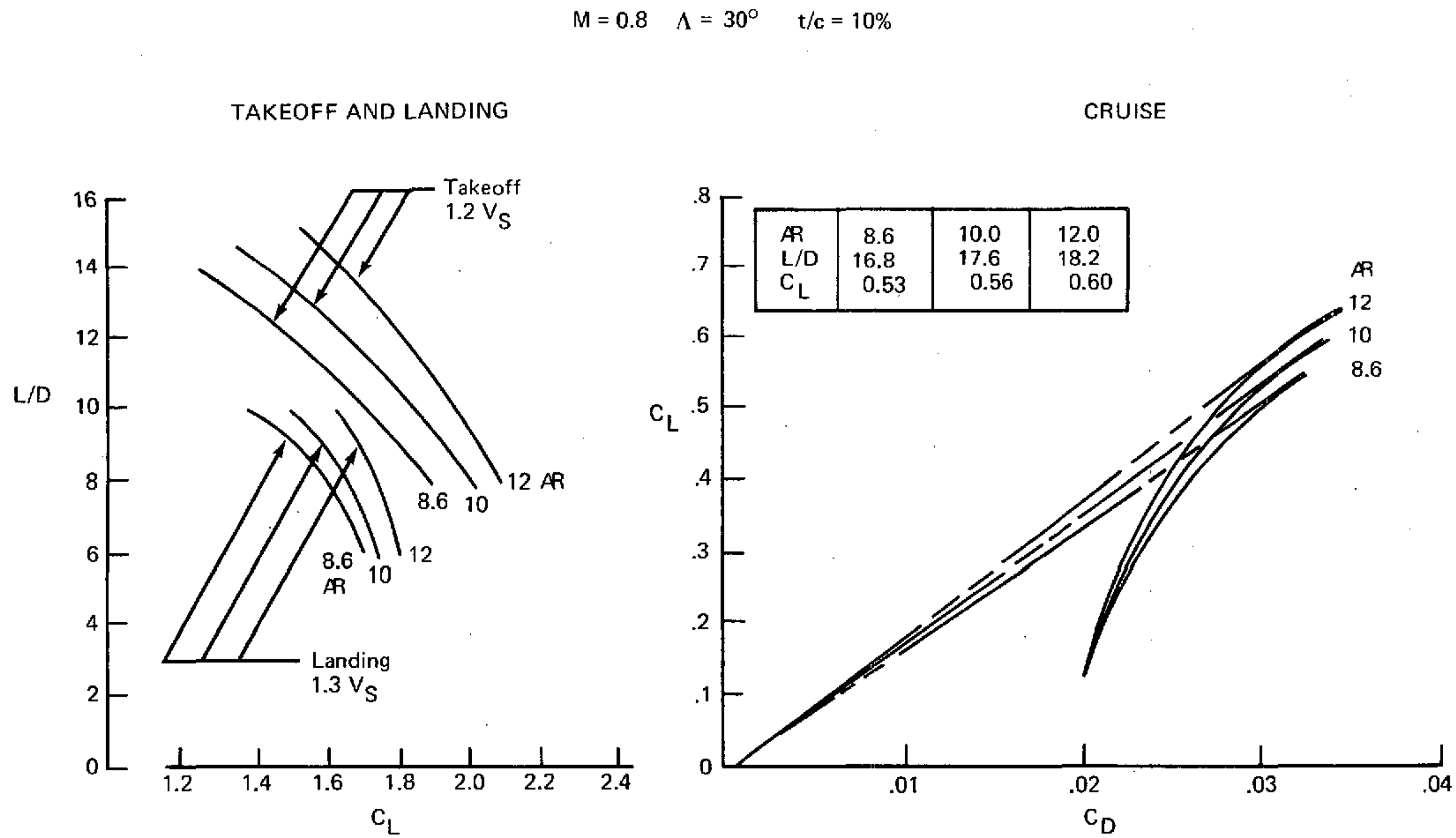


Figure 27.—Aerodynamic Effects of Increased Aspect Ratio

AR = 8.6

M	0.73	0.8	0.9
Λ	10°	30°	37.5°
t/c	0.13	0.10	0.08

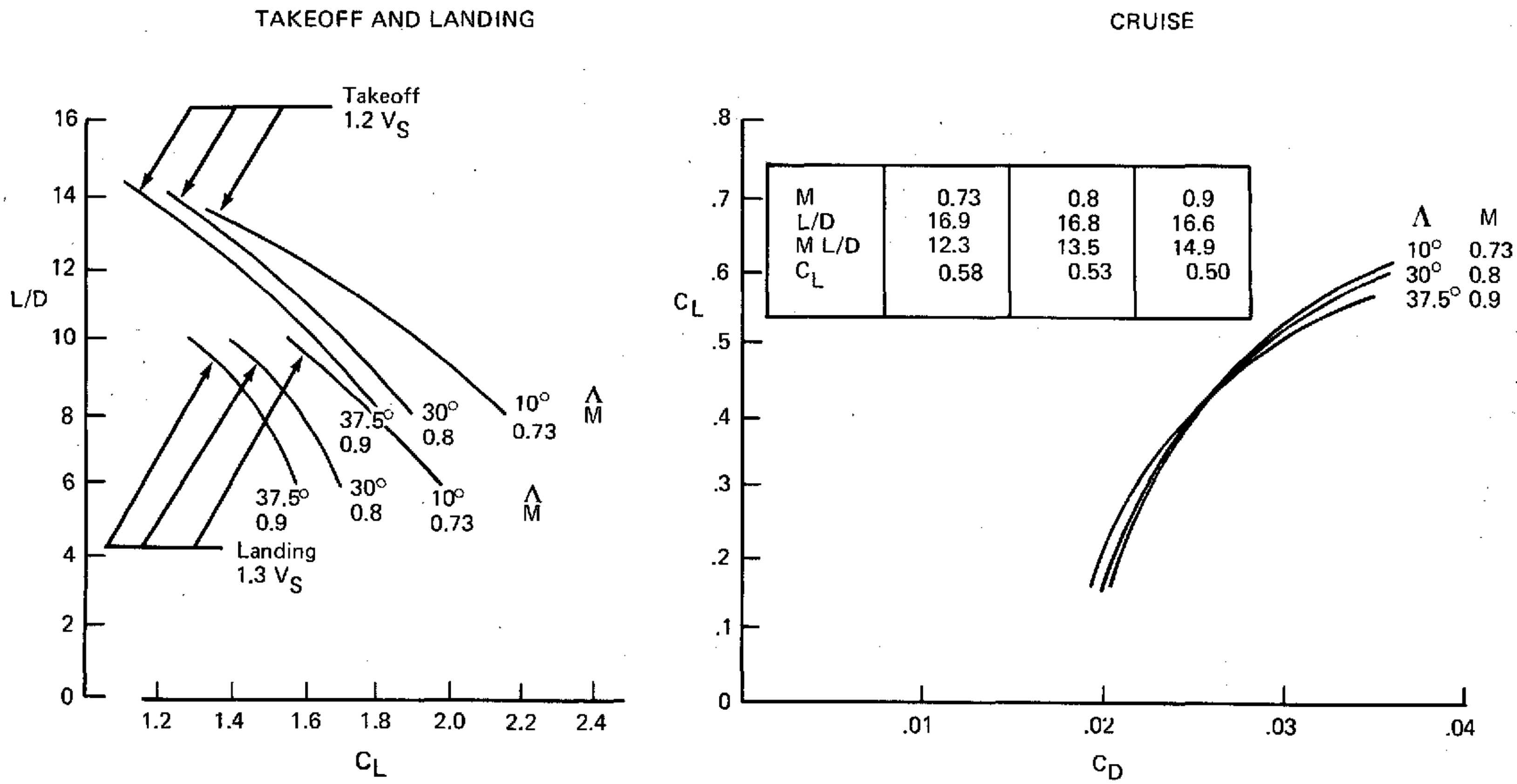


Figure 28.—Aerodynamic Effects of Cruise Speed

For each wing geometry-cruise speed point, an airplane configuration was sized with the following major objectives and constraints:

Payload	=	18 140 kg (40 000 lb) 196 passengers.
Range	=	5556 km (3000 nmi) still air
Engine cycle	=	BPR 6 conventional turbofan
Cruise altitude	$\geqslant$	9144 m (30 000 ft)
Takeoff field length	=	2530 m (8300 ft) [at 305 m, 305 K (1000 ft, 90° F)]
Approach speed	$\leqslant$	69 m/s (135 kn) maximum landing weight

Within these objectives and constraints, both wing and thrust loading were selected for minimum fuel usage as shown in figure 29 for Mach 0.8 cruise, wing AR = 12, $\Lambda = 30°$, t/c = 10% airplane. In this particular case, the "minimum fuel" airplane coincides with the takeoff field length (TOFL) and V_{APP} constraints and cruises at a C_L of about 97% of that for L/D_{MAX}. Since the object of the sensitivity studies was to determine trends, all fuel usage, economics, and noise data are shown relative to this airplane (fig. 30).

4.3.3.2 Airplane Analysis Methods

Aerodynamics—Low-Speed Data.—The low speed aerodynamic data for the airplanes correspond to that used in the reference 2 study. The low-speed data were calculated using established methods for the assumed flap geometries and were based upon available wind tunnel data from similar configurations. The basic flap system consisted of cambered leading-edge devices and double-slotted main-aft trailing-edge flaps. The trailing-edge flaps are externally supported with the tracks covered by fairings. These flap systems were selected during the reference 2 program after the study of several candidate systems. The aspects of flap design investigated were: (1) the effect on TOGW and OEW for a given mission, (2) price, (3) maintainability and reliability, and (4) productivity. The selected systems appeared to offer the best compromise between the various aspects investigated.

Low-speed operational envelopes (L/D versus C_L) for the airplanes developed under the current study are shown for both takeoff and landing in figures 27 and 28. Each of the airplanes essentially uses the basic TAC flap system adapted to the specific wing planform. The critical flap geometric characteristics are the same for all the airplanes so that the differences in low-speed performance are due mainly to variations in wing sweep and aspect ratio.

Aerodynamics—High-Speed Drag Polars.—The high-speed drag polars for the present study airplanes have been developed by the contractor using established methods based upon experience with subsonic jet airplanes. The basic airfoil used was an advanced technology design developed by the contractor and verified by wind tunnel tests. This advanced airfoil

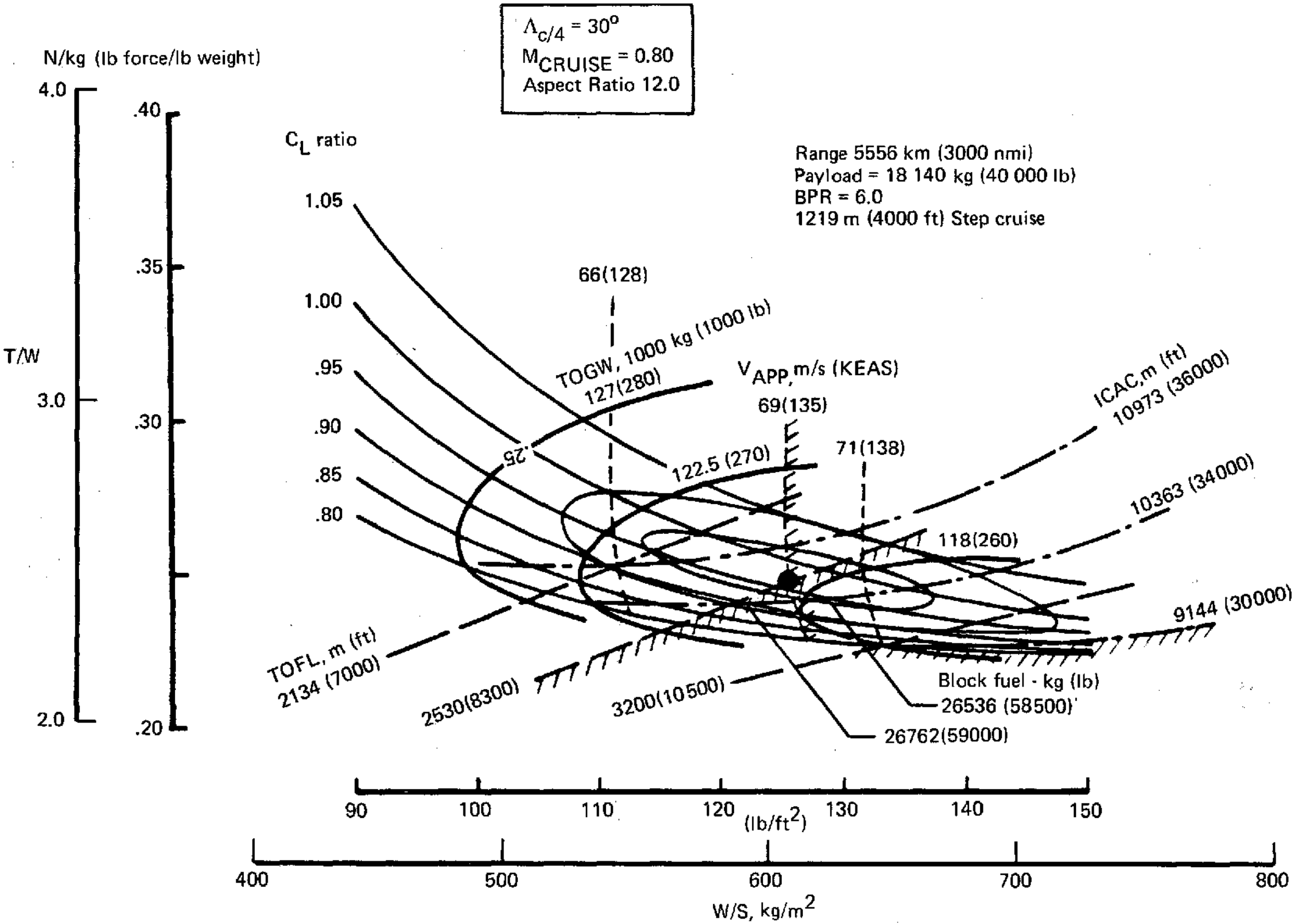


Figure 29.—Design Point Selection, Energy Influence

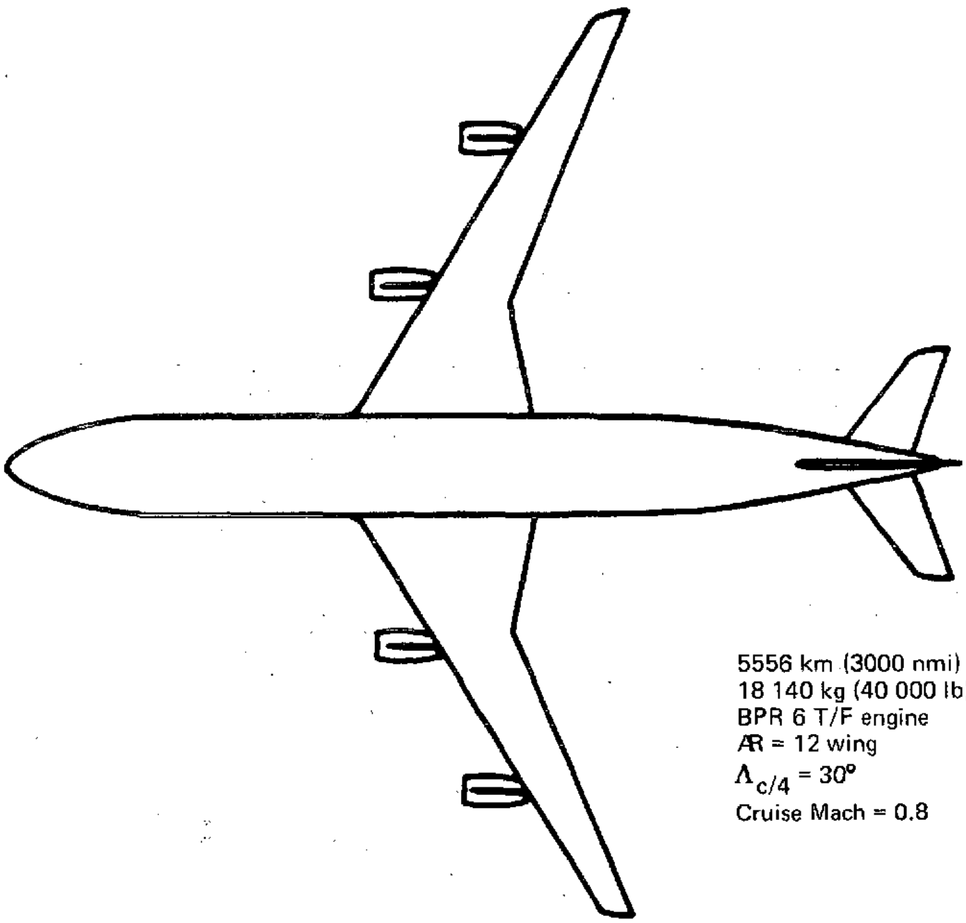


Figure 30.—Parametric Configuration Base

was developed for a Mach 0.84 subsonic airplane with a design cruise $C_L \approx 0.45$. Using this airfoil, the required outboard wing thickness versus cruise Mach and wing sweep are as follows:

M	$\Lambda_{c/4}$	t/c
0.70	10°	17%
0.71	10°	15%
0.73	10°	13%
0.80	25°	8%
0.80	30°	10%
0.80	35°	12%
0.90	37.5°	8%

Typical cruise drag polars illustrating the effects of AR, sweep, and thickness are shown in figures 27 and 28.

A correlation of cruise L/D in terms of wing span and total wetted area is shown in figure 31.

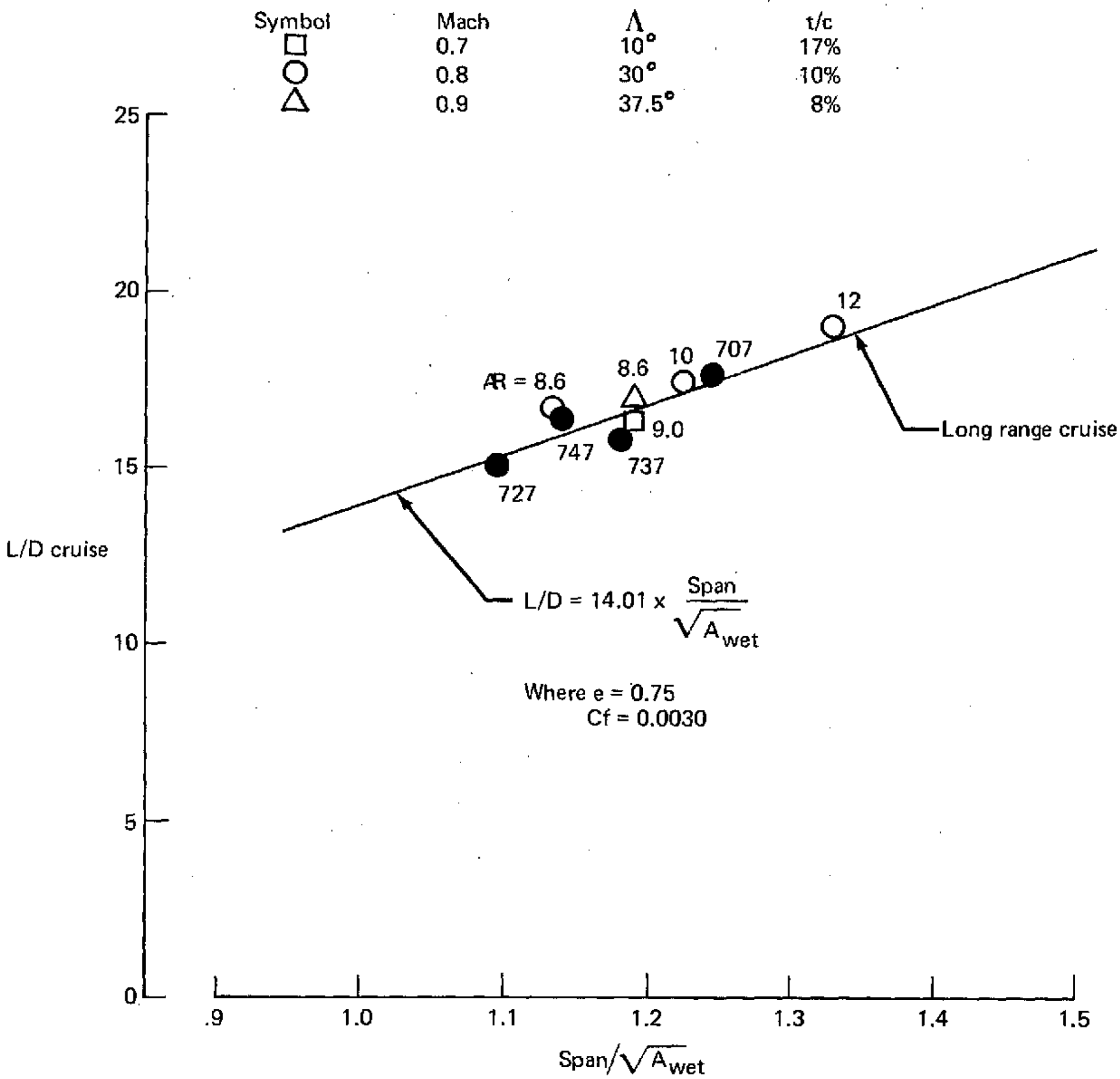


Figure 31.—Effect of Wetted Area and Span on Cruise Efficiency

4.3.3.3 Airplane Analysis Results

Figure 32 shows the results of the wing AR study at a cruise Mach number of 0.8 in terms of relative fuel usage, economics (DOC), and noise (EPNdB "traded" with respect to FAR 36 regulations). These data show that fuel usage was improved about 6% by increasing AR from 8.6 to 12. The highest AR wing (fig. 29) just met the landing approach speed constraint, while the lower AR wings had somewhat lower approach speeds. This suggested that a simpler and/or smaller flap system could improve the fuel usage at lower AR's. As wing AR is increased, it was also felt that a detailed study would show the desirability of increasing wing taper ratio with increased AR. Refinements in trim-drag and tail-sizing criteria could also have an impact on this trend. It was estimated that the major effect could be through the incorporation of a simpler flap system which could reduce the benefits shown for increased AR by one half. Increasing AR from 8.6 to 12 improves the relative DOC about 1% at the baseline fuel price of 5.8¢/liter (22¢/gal) and 2% if fuel price is doubled. Relative noise levels are virtually unchanged with increased AR. Results of increased wing AR at a cruise Mach of 0.7 show very similar trends. Also shown at the top of figure 32 is the influence of incorporating two levels of advanced technology structure. The trends are similar but with a slightly greater improvement at the highest AR shown (12) due to the removal of most of the wing flutter weight penalty.

The optimization of AR at the higher values shown in this study is thought to be due to several basic assumptions and ground rules:

- Four engines on the wing–the outboard engine provides dead weight relief and minimizes the flutter weight penalty. This would not apply to a three- or two-engine airplane.

- Taper ratio was held constant at 0.25–a more detailed investigation is required of structure space available at the outboard engine location. Inadequate space could result in increased taper ratio required and increased weight.

- Availability of integrated airfoil–wing designed to operate at the desired high C_L's with the assumed drag levels. Wind tunnel data are needed to substantiate the theoretically predicted drag levels.

4.3.3.4 Effect of Reducing Cruise Speed

Figures 33 and 34 show the initial results of the cruise speed study. The $M = 0.8$, $AR = 12$, $\Lambda = 30°$, $t/c = 10\%$ design had about 12% lower fuel usage than the $M = 0.9$, $AR = 8.6$, $\Lambda = 37.5°$, $t/c = 8\%$ design. This was expected based upon previous studies in this speed range. The relative DOC was unchanged while the traded noise level improved about 3 EPNdB because of the effect of the decreased wing sweep on takeoff and landing performance. The first Mach 0.7 design had a slightly swept wing (10°) and a maximum t/c consistent with the cruise Mach number. The results showed this airplane to have about 7% higher fuel usage than the Mach 0.8 design, poorer economics (2%), and lower noise (2 EPNdB) because of the decreased wing sweep effects. At this point sweep-thickness trades at both $M = 0.7$ and 0.8 were conducted to determine the best wing geometry choice at each Mach number. The results of this study are shown in figure 35. Thinning the 10°

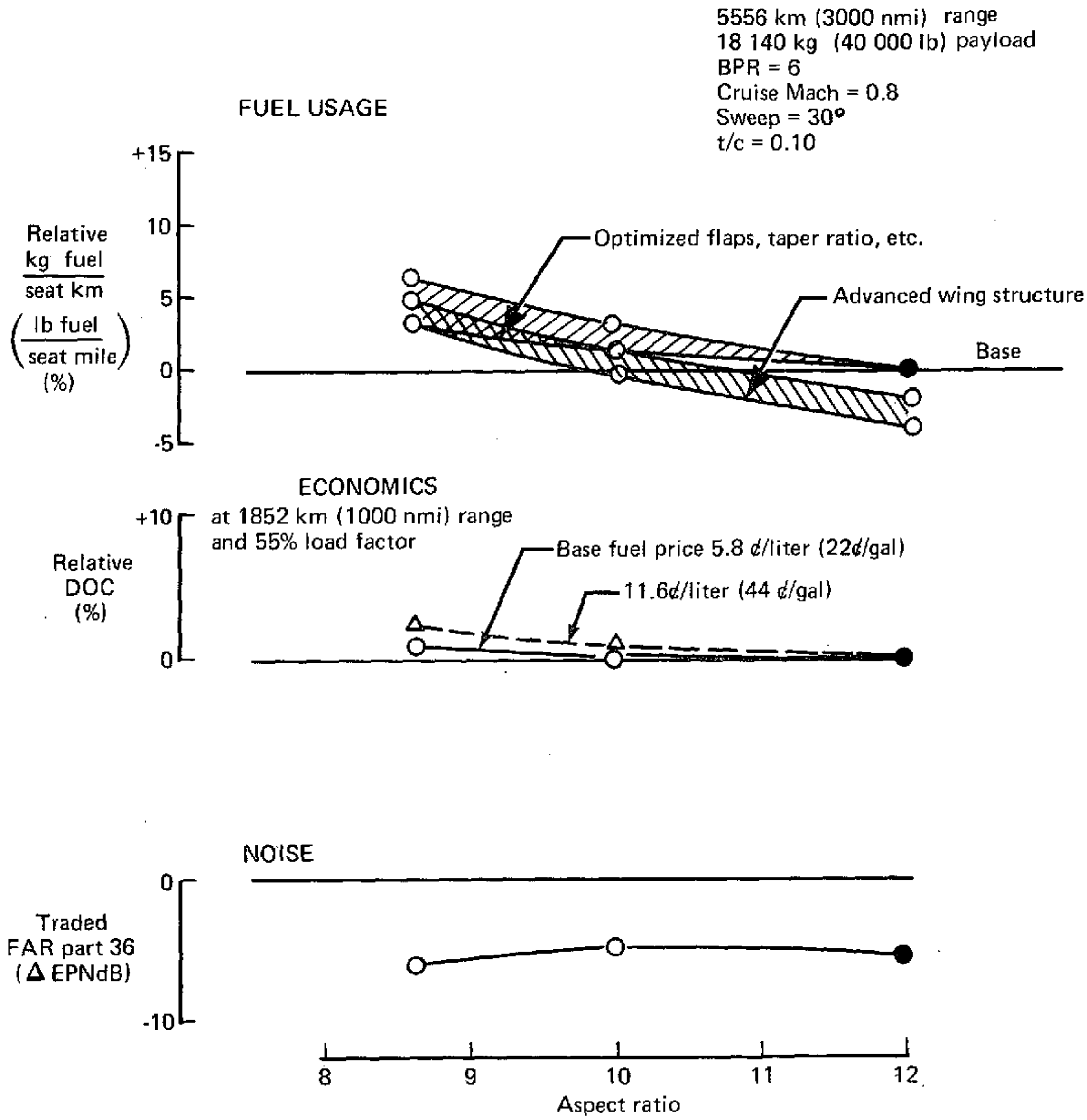


Figure 32.—Airplane Performance With Varying Aspect Ratio

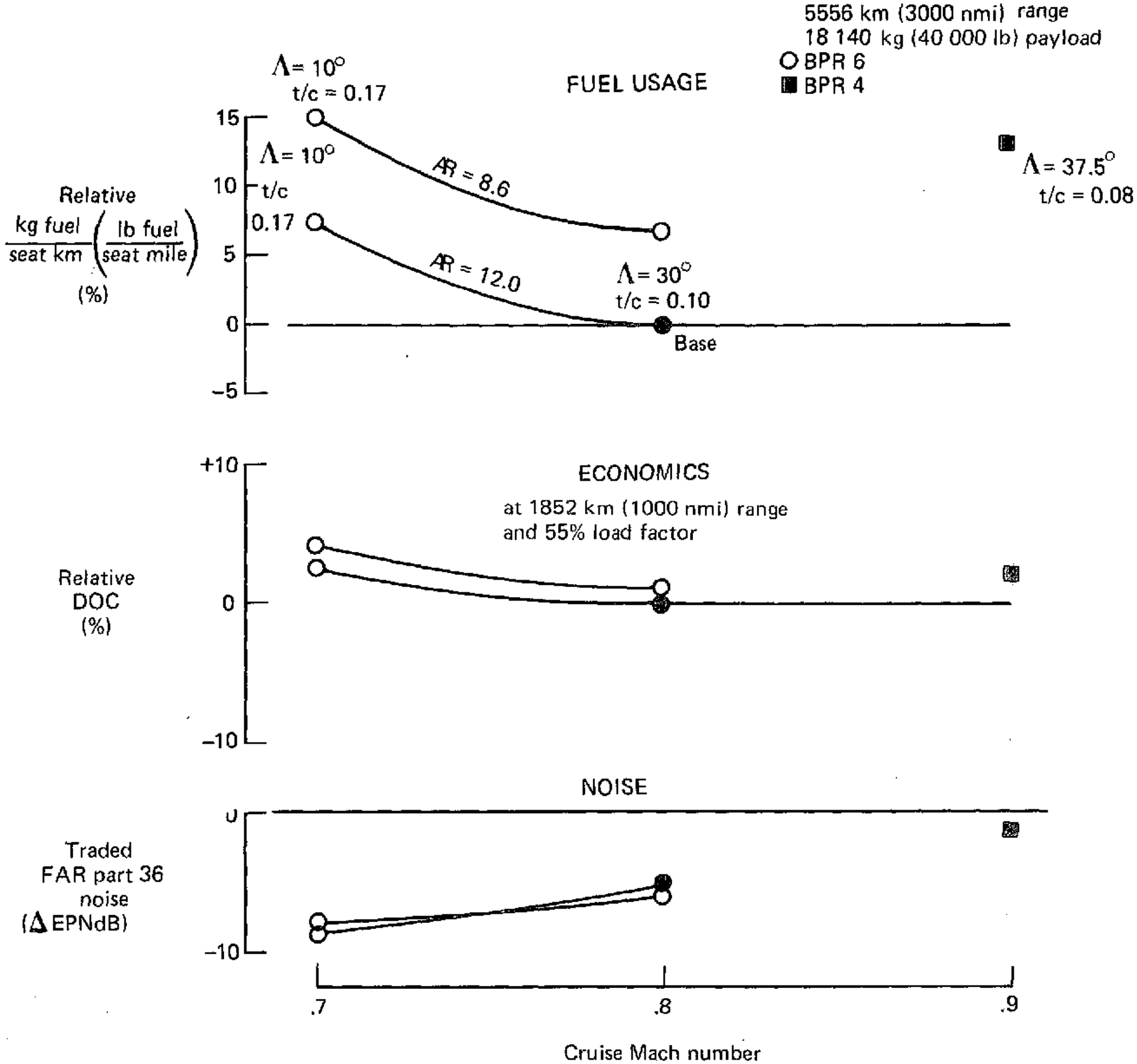


Figure 33.—Airplane Performance With Varying Cruise Speed, Sweep, and t/c

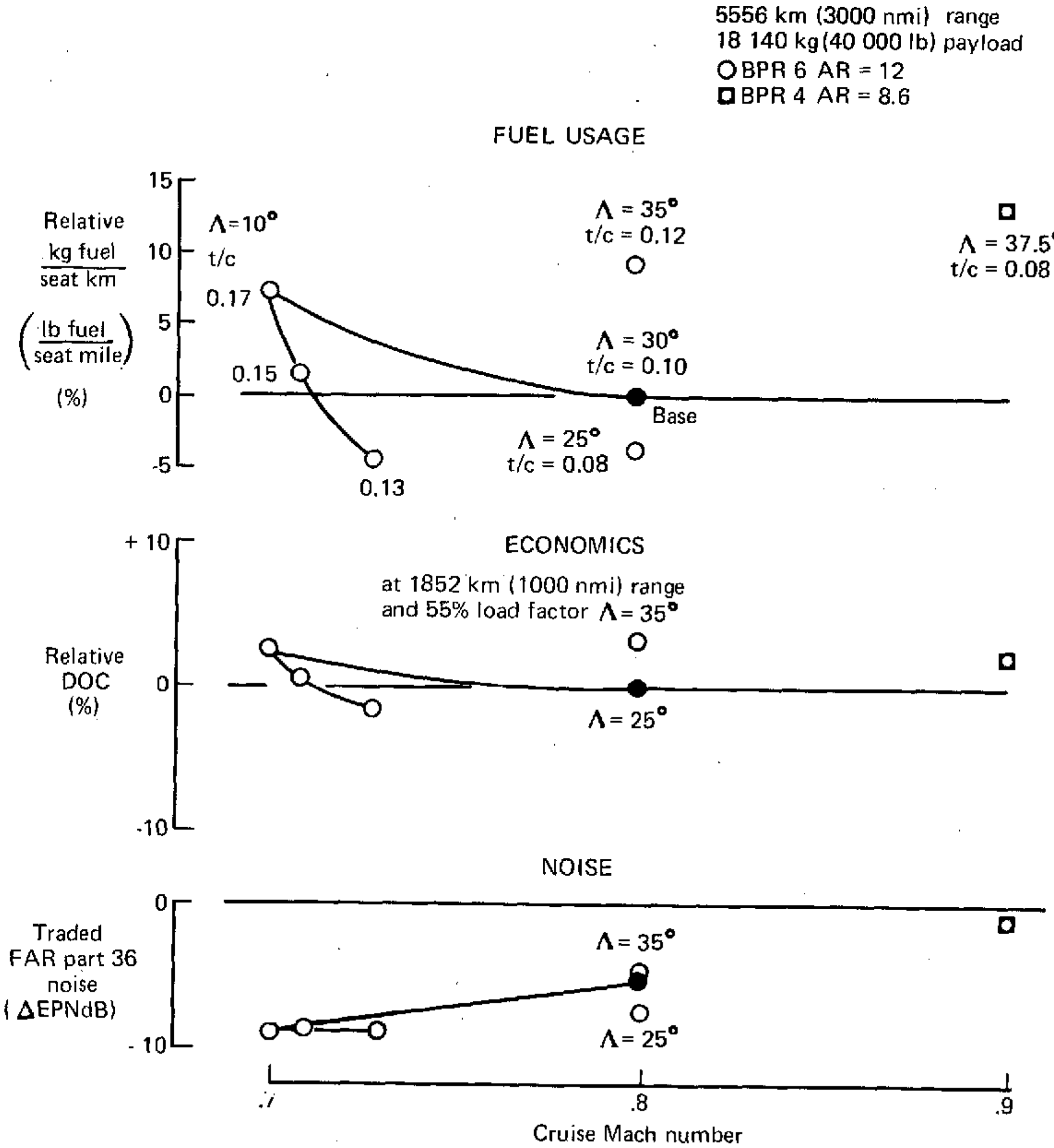


Figure 34.—Airplane Performance With Varying Cruise Speed, Sweep, and t/c

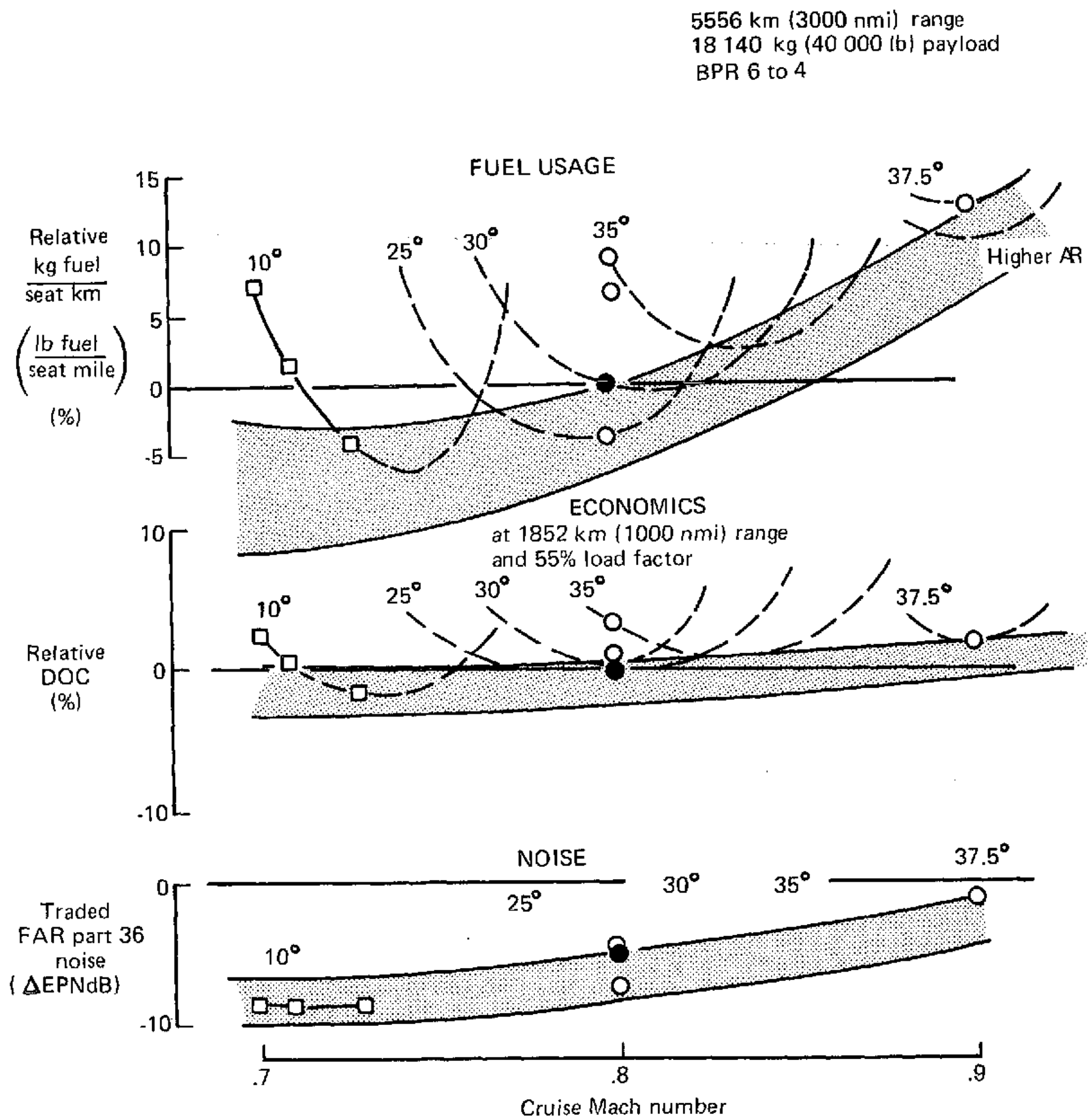


Figure 35.—Airplane Performance Possible Trends

swept wing from 17% to 13% and increasing cruise Mach 0.73 caused a large (12%) improvement in fuel usage and economics (4%). Similarly, thinning the Mach 0.8 wing from 10% to 8% and decreasing the sweep from 30° to 25° showed a modest (4%) improvement in fuel usage and noise (2 EPNdB).

Although specific "buckets" were not established for each wing sweep, the results of these studies lead to some possible trends with design cruise speed as shown in figure 35. Decreasing cruise speed from M = 0.9 to 0.8 produces a large improvement in fuel usage (18%) with little change in DOC and an improvement of about 4 EPNdB in traded noise. The magnitude of improvement for further reduction in cruise speed depends upon more detailed studies of the effects of low sweep and thickness. In addition, the effects of possible improvements in aerodynamic wing design (wings designed for higher cruise C_L's desired at reduced cruise speeds) could have a large impact on these trends. There is a critical need for wing aerodynamics data before such trends can be determined with a satisfactory degree of confidence.

4.3.4 Wing Geometry-Cruise Speed Selection

With low fuel usage as a prime new design objective, the results of the wing geometry-cruise speed sensitivity studies (fig. 36) indicate that, for these design payload/range objectives and field length/cruise altitude constraints, it appeared desirable to decrease the cruise speed of the TAC airplane from M = 0.9 to 0.8, increase the AR to 12, decrease the Λ to 25°, and retain the thin wing. Whether or not substantially greater fuel savings could occur by further decreases in cruise speed is not known. These data show that the fuel burned at Mach 0.73 is almost the same as at Mach 0.8, while noise and economics are virtually the same. Hence, based on these data there did not appear to be reason for a reduction in speed below Mach 0.8. In any case, other considerations, such as the general comments by the participating airlines on the undesirability of reducing cruise speeds below current levels, would have to be given careful consideration before such a choice were made.

4.4 ENGINE CYCLE STUDIES

4.4.1 INTRODUCTION

Engine cycle studies were conducted to determine the fuel saving advantages of conventional turbofans with BPR's higher than originally used on the TAC aircraft. The BPR from these studies was intended to yield the engine with highest fuel savings potential and also establish a baseline for a conventional cycle against which unconventional or advanced engine cycles could be compared. Unconventional engine types that were initially screened included multicycle engine, geared fan, regenerative fan or turboprop, advanced technology turboprop, variable-pitch fan, and high OPR turbofan.

To assure the validity of the conventional engine data base developed for the airplane sensitivity studies for a 1980-85 airplane certification period, reviews of the contractor-developed turbofan engine data were held with NASA-Lewis, NASA-Langley, P&WA (subcontractor), and two other major engine manufacturers. Airlines were consulted for

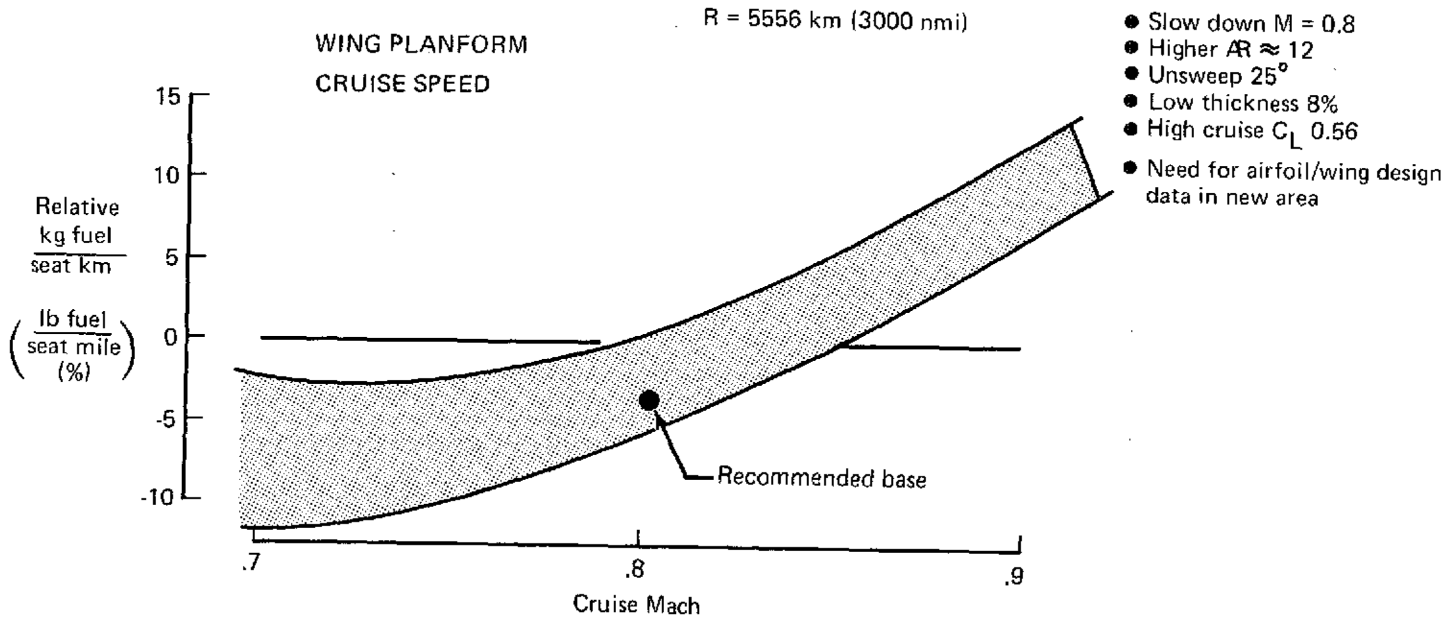


Figure 36.—Sensitivity Studies Results

their comments on engine maintenance. In addition, a recent NASA study (ref. 6) on the economic effects of propulsion systems technology on transport aircraft is reflected in the propulsion data.

For the advanced engine cycles having fuel saving potential, initial cycle analysis and airplane sensitivity studies were conducted. Reviews were held with NASA-Lewis, NASA-Langley, and P&WA. Based on these studies and with NASA-Langley approval, the advanced technology turboprop, variable-pitch fan, and high OPR turbofan were selected for airplane evaluation. Consultation was held with the airlines to obtain their views on engine maintenance and operation for use in the economic analysis. The engine subcontractor subsequently supplied the advanced engine data that were used in the airplane evaluation.

4.4.2 CONVENTIONAL ENGINES

The optimum cycle for a conventional turbofan engine depends on the design cruise Mach number. As the design speed is reduced from 0.98 and 0.90 as in the ATT and TAC studies (refs. 1 and 2), it was found that the values of fan pressure ratio appropriate for those speeds result in jet velocities which are too high for the most economical operation at lower cruise speeds. Determination of the optimum BPR (and fan pressure ratio) for any particular cruise speed is an iteration process, since improved SFC can only be achieved at a lower thrust per unit engine size and greater engine weight. This was the subject of the BPR study.

To provide a data base for this study, the performance of a family of conventional turbofan engines was calculated. This engine family was designed for BPR's of 4, 6, 8, 10, and 12 at design cruise Mach numbers of 0.6, 0.7, 0.8, and 0.9.

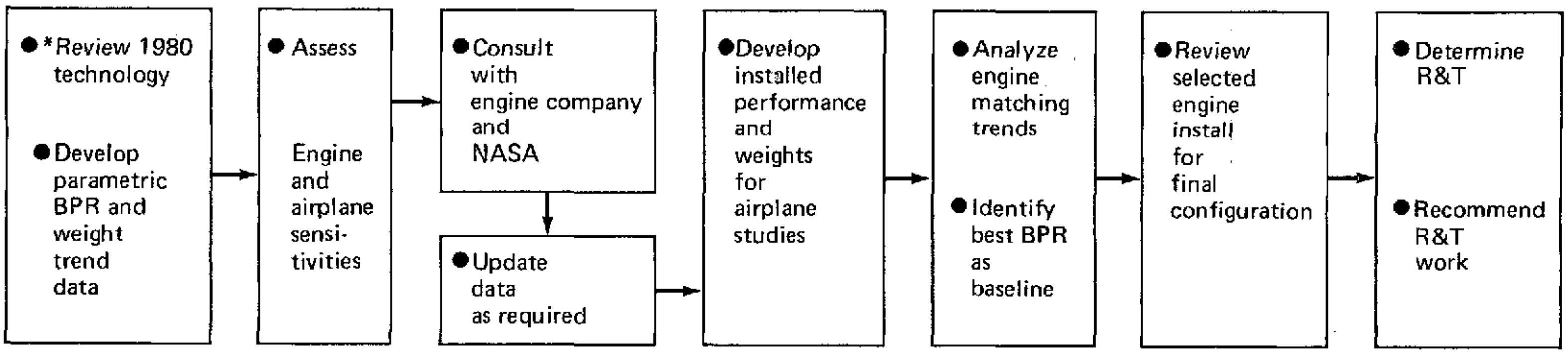
4.4.2.1 Technical Approach

The technical approach followed is shown in figure 37. The engine technology level was selected to be consistent with a 1980-85 airplane certification date.

4.4.2.2 Engine Cycle Assumptions

Based on need for low emissions, primarily NO_X formation, the overall compressor pressure ratio was selected to be 24 to 1 at the design point. The engine design point was set at the maximum cruise, thrust rating, 9144 m (30 000 ft), on a standard temperature day. Existing parametric engine studies, such as shown in figure 38, were initially reviewed to determine the fuel saving potential. Airplane TOGW and block fuel sensitivity factors obtained from the reference 1 study were used in conjunction with the engine data to obtain the airplane sensitivity results shown in figure 39. On the basis of this study and the economic effects on engine hot-section maintenance and price, the maximum turbine-rotor inlet temperature was selected to be 1560 K (2800° R) at takeoff and 1420 K (2550° R) at the cruise design point.

The engine component assumptions are shown in table 6. The design point performance was then calculated for a family of turbofan engines having BPR's of 4, 6, 8, 10, and 12 and Mach numbers at 0.6, 0.7, 0.8, and 0.9. For each BPR and Mach number, the fan pressure



*Consistent with 1980-1985 airplane certification

Figure 37.—Technical Approach Conventional Turbofans

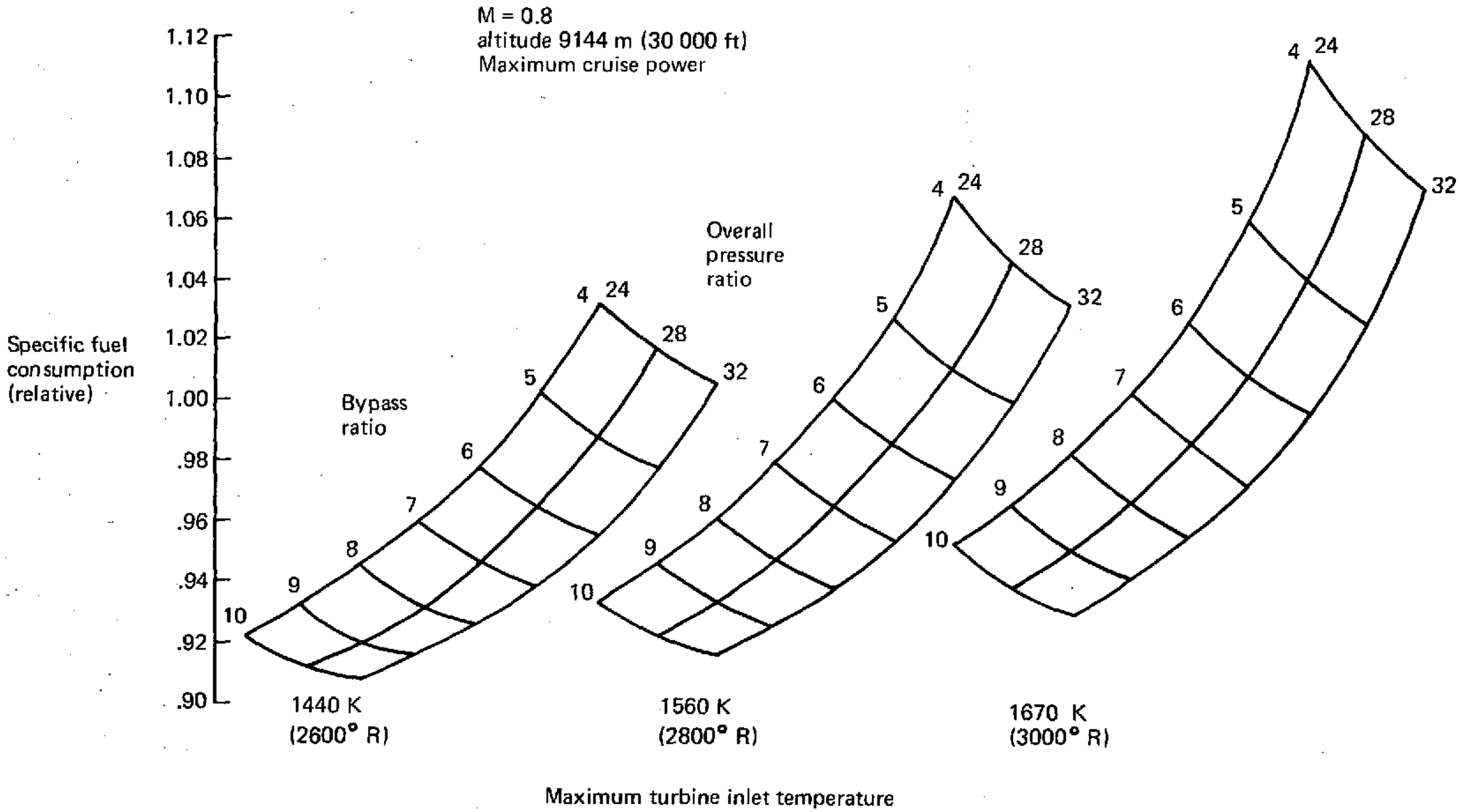


Figure 38.—Uninstalled Engine Performance Comparison

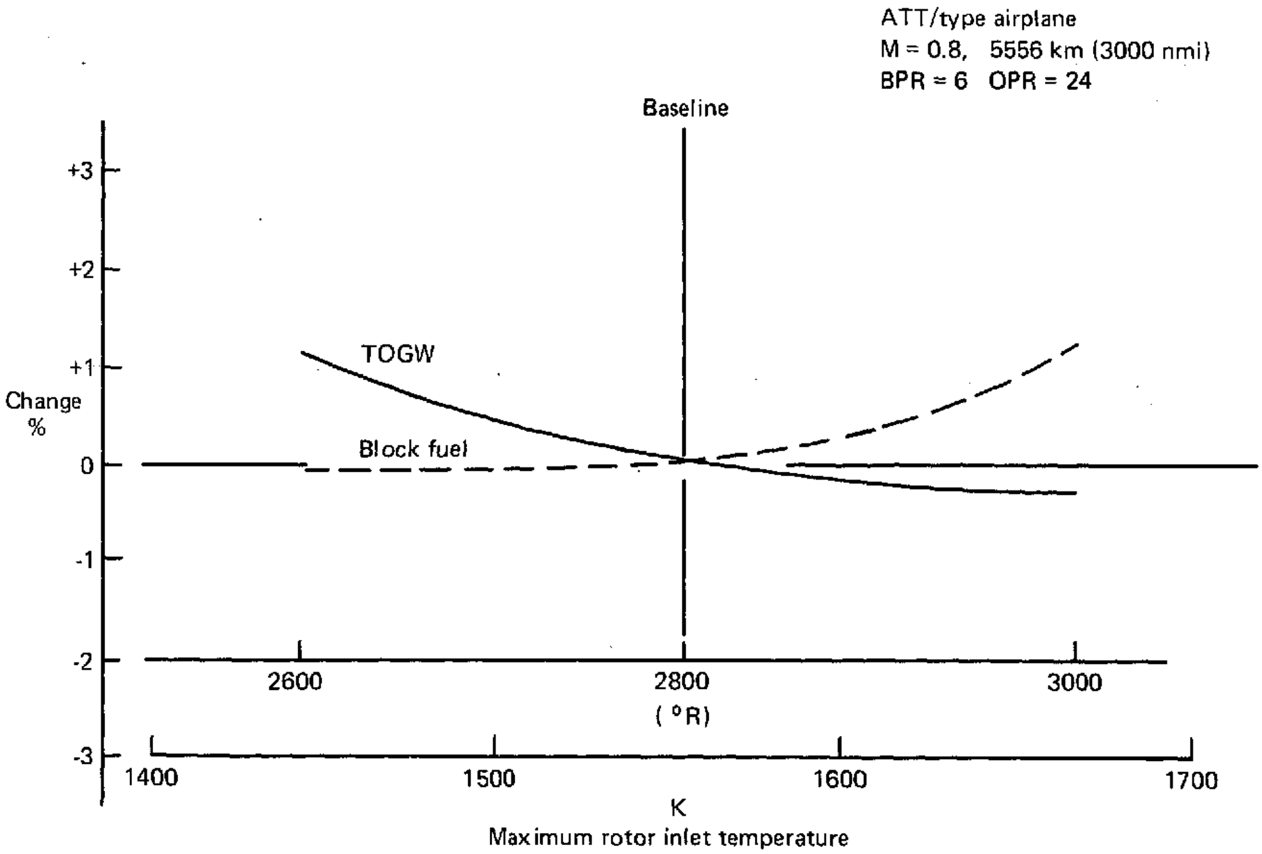


Figure 39.—Effect of T_4 on Takeoff Gross Weight and Block Fuel

ratio was optimized to achieve maximum cruise thrust per unit airflow and minimum cruise SFC. The resulting values of fan pressure ratio for a design M = 0.8 are shown on the lower portion of table 6.

4.4.2.3 Parametric Engine Performance Data

Each engine was initially sized to provide an uninstalled thrust of 133 000 N (30 000 lb) at sea level, zero speed, with an ambient temperature of 29°C (84°F). The installed performance was then calculated for takeoff, climb, and cruise for each of the engines. The installation losses include those due to airbleed (0.907 kg/sec or 2.0 lb/sec) from an intermediate compressor stage, where the pressure ratio is 7 to 1, and those due to power extraction for driving the airplane accessories (48.5 kW or 65 hp). Installed performance does not include the penalty for nacelle external drag unless specifically noted.

Takeoff thrust versus speed for the Mach 0.8 design point engines is shown in figure 40. The ratio of cruise to takeoff thrust (at zero speed) is shown in figure 41. This parameter is particularly significant when the engine size is dictated by the cruise thrust requirement. For convenience, the cruise SFC has been converted into the range factor parameter V/SFC and

Table 6.—Conventional Turbofan Cycle Assumptions

General assumptions at design point		
Overall compressor pressure ratio	24.0	
Fan specific flow rate	200	kg/sec – m^2 (41.0 lb/sec–ft^2)
Fan hub/tip ratio	0.38	
High pressure compressor polytropic efficiency	0.89	
Combustor efficiency	0.995	
Combustor pressure loss, %	4.2	
Turbine inlet temperature	1420 K (2550°R)	
High pressure turbine cooling, % of HPC flow	5.5	
Low pressure turbine cooling, % of HPC flow	1.4	
High pressure turbine adiabatic efficiency	0.90	
Low pressure turbine, efficiency	0.91	
Shaft efficiencies	0.995	
Nozzle discharge coefficients	1.0	
Primary nozzle velocity coefficient	0.99	
Primary duct pressure loss , %	0.6	

Optimum design point fan pressure ratio – M = 0.80

Bypass Ratio	4	6	8	10	12
Fan pressure ratio	1.85	1.66	1.525	1.425	1.37
Fan adiabatic efficiency	0.815	0.836	0.857	0.870	0.879
Fan duct pressure loss, %	2.2	1.85	1.6	1.4	1.2
Fan nozzle velocity coefficient	0.9905	0.9925	0.9934	0.9938	0.9939

Note: 9144 m (30 000 ft) Maximum cruise thrust Standard day

plotted against cruise Mach number in figure 42. This parameter is proportional to the overall engine efficiency. The favorable effect of airplane speed on engine efficiency is evident.

4.4.2.4 Engine Weights

Reviews of 1980-85 inservice engine weight technology with the engine subcontractor were conducted to determine the level of engine weights to be used in the BPR study. The weight technology level finally assumed for this study is shown in figure 43. For comparison, weight data for existing high-bypass engines or those in development were spotted on the curve. These data were scaled to 133 000 N (30 000 lb) static takeoff thrust for consistency. It was assumed that for the BPR study, a mean line through the band would reflect a reasonable balance between engine weight, price, and maintenance cost for the 1980-85 airplane certification time period.

During the above evaluation, account was taken of the results of a recent NASA-sponsored study (ref. 6) that showed the importance of engine maintenance relative to engine weight on airline operations and economics. In summary, one of the prime conclusions of that study was that engine weight could be compromised to achieve better maintenance with an overall beneficial effect on economics. That criterion was applied in this study. The engine

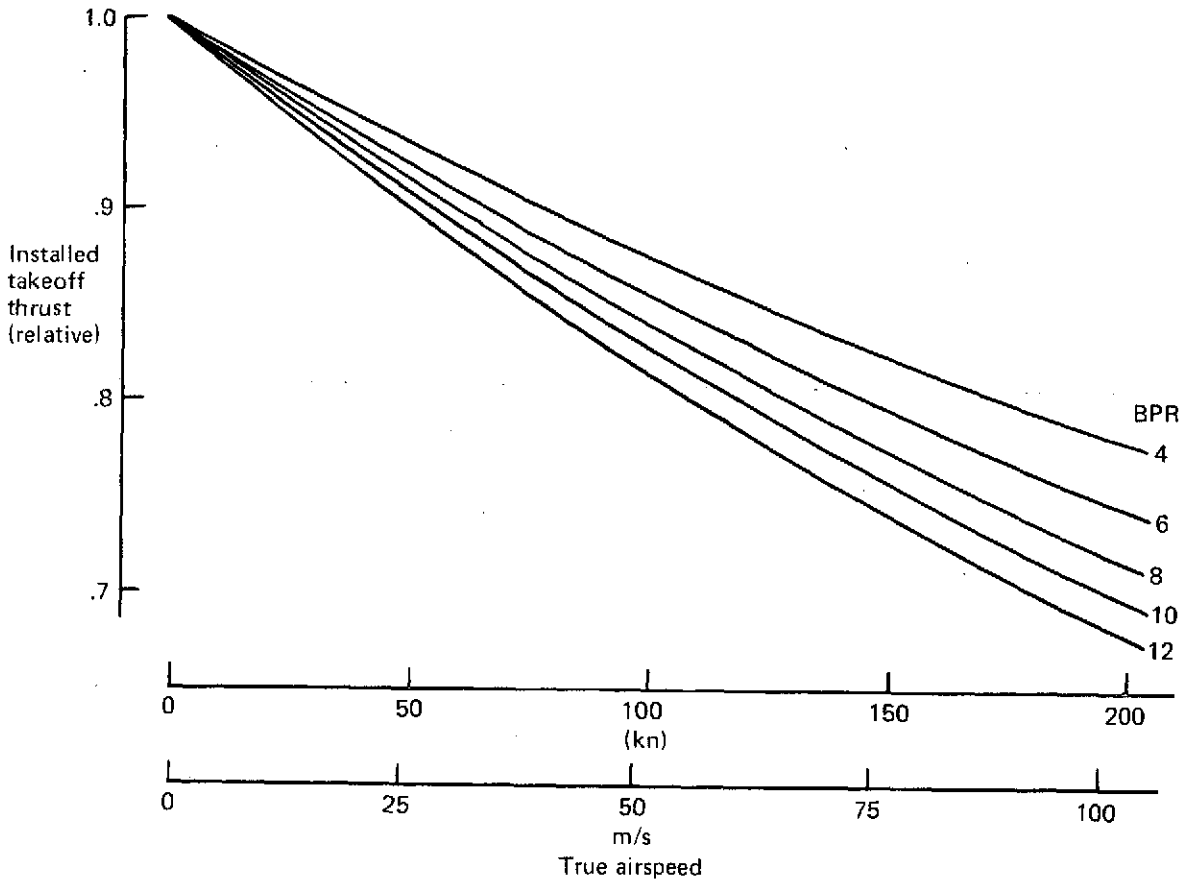


Figure 40.—Takeoff Thrust Versus Airspeed, Parametric Engines

weight data used in this study are, therefore, not as optimistic as the data used in the previous ATT program (ref. 1).

4.4.2.5 Engine Manufacturers Comments

Prior to starting the airplane studies, the parametric engine data package was provided to each of the three large engine manufacturers for review; their comments are shown in table 7. Two of the manufacturers believed higher turbine inlet temperatures were appropriate, and two thought the engine weights projected were too high. Since these recommendations were not consistent with improved engine reliability and maintainability for the 1980-85 time period, they were not adopted.

4.4.2.6 Results of Bypass Ratio Study

Engine scaling rules for dimensions, weights, and performance were established for the airplane studies. For 196 passengers, the airbleed per engine was established at 0.64 kg/sec (1.4 lb/sec) and the power extraction at 48.5 kW or 65 hp for all engine sizes.

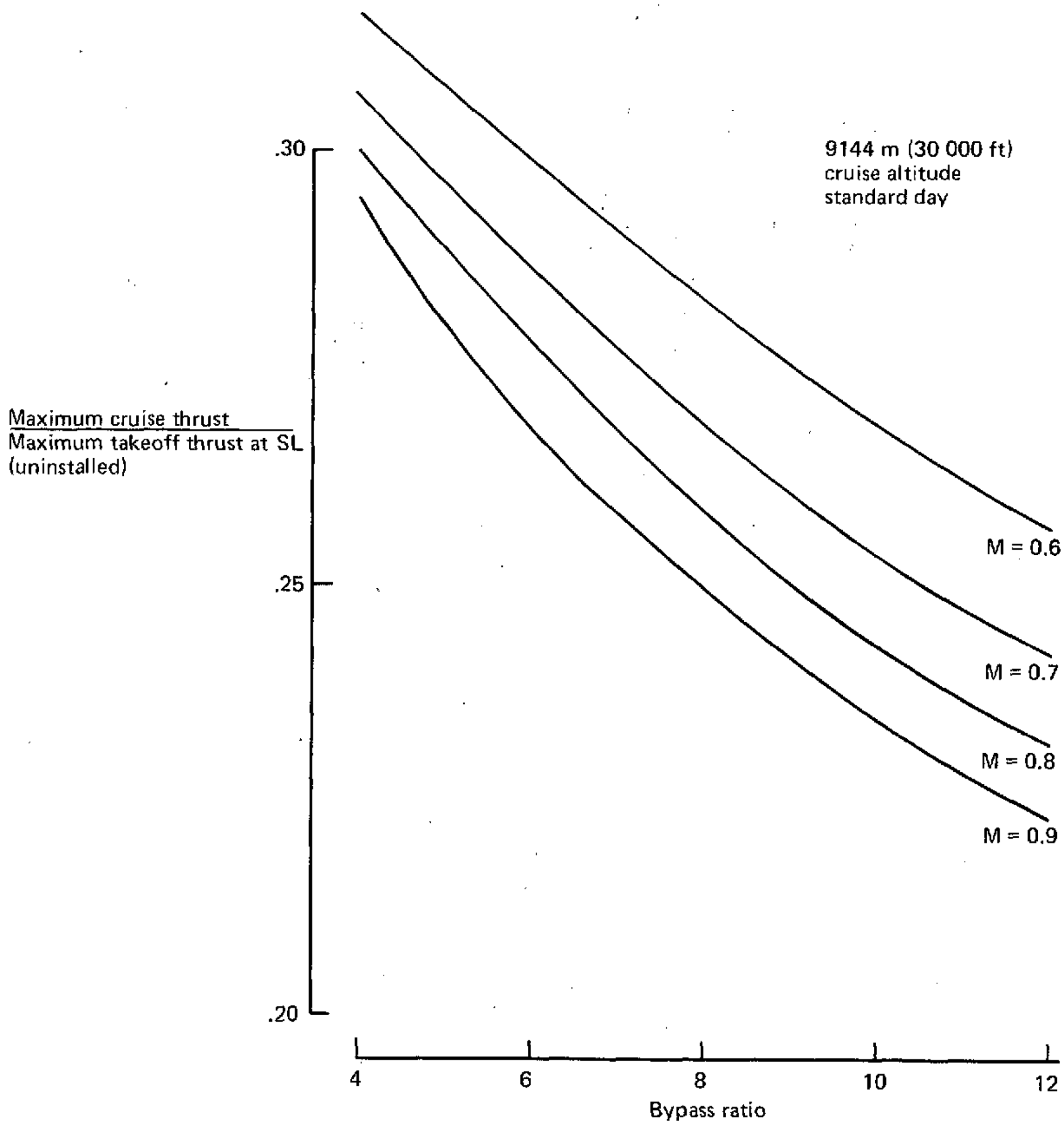


Figure 41.—Thrust Lapse Rate, Parametric Engines

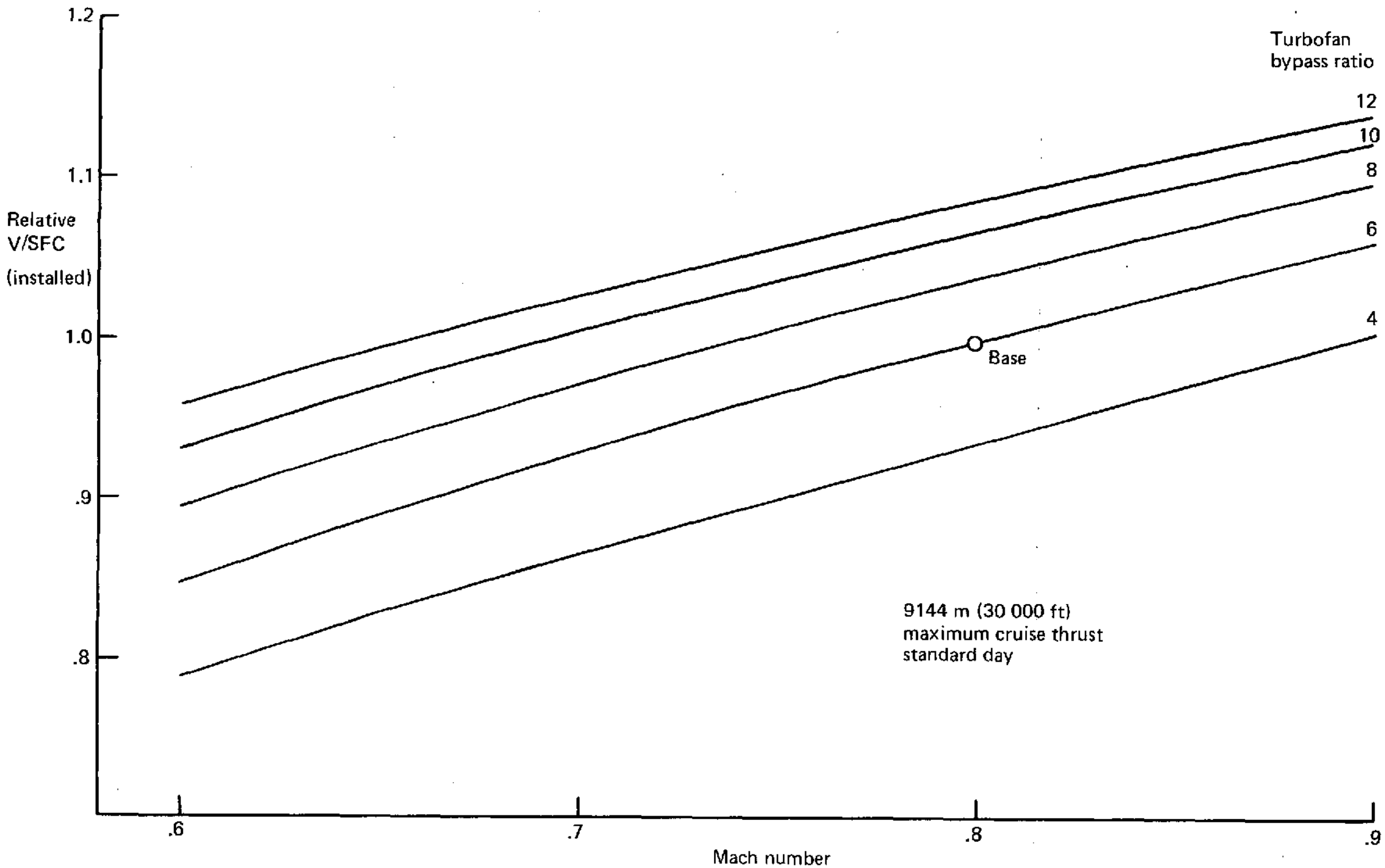


Figure 42.—V/SFC Versus Bypass Ratio

SLS thrust 133 000 N (30 000 lb)

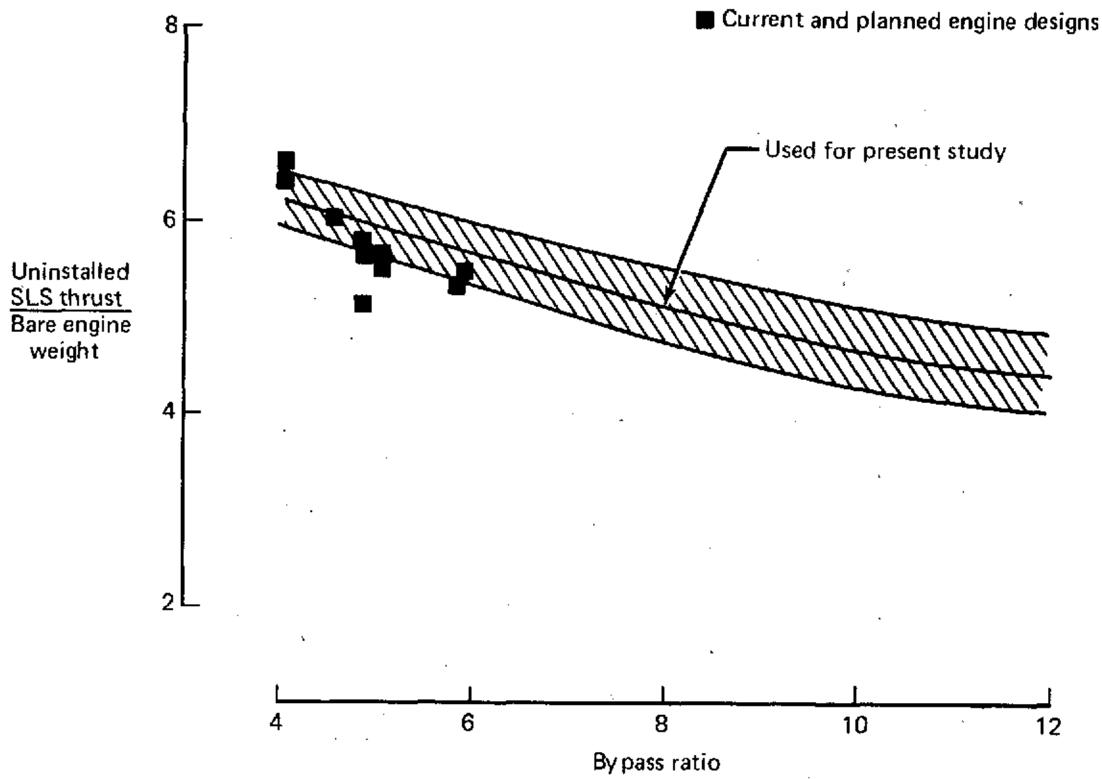


Figure 43.—Takeoff Thrust/Engine Weight

The BPR study was conducted for a cruise speed of M = 0.8. The maximum allowable takeoff field length and/or approach speed was set at 2930 m (8300 ft) and 69.5 m/sec (135 kn), respectively. The wing AR was fixed at 12 with a wing sweep of 30°.

The required takeoff thrust for each of the matched airplanes is shown in the upper portion of figure 44. At BPR 6 and above, the engines are sized by the cruise thrust requirement. Since the higher BPR's have a lower cruise thrust in relation to their takeoff thrust (fig. 41), the available takeoff thrust increases substantially at the higher BPR's. The effect of some increase in matched airplane TOGW is also reflected at the higher BPR's. The relative pod (engine, nacelle, and reverser) weights are shown on the lower portion of figure 44. The dashed line reflects the portion of the weight increase that is due to (1) the lower takeoff thrust to weight ratio of the higher bypass engines (fig. 44), and (2) the increased nacelle and reverser weights for engines having lower specific thrust.

Table 7.—Engine Manufacturer's Comments on Boeing Conventional Parametric Engine Cycles

Category	Boeing performance for BPR = 6 cycle	Comments		
		P&WA	Engine company A	Engine company B
Overall cycle characteristics	OPR = 24	OPR = 25 (24 okay for NO_x)	OPR = 38	— —
	T_4 T/O = 1560 K (2800° R)	Agree	Higher T_4	T_4 low by 33° to 56°C (60° to 100°F)
	T_4 CRU = 1420 K (2550° R)	Agree	— —	— —
	FPR = 1.66	Agree	— —	— —
Ratings		Agree	Agree	Agree
Cycle assumptions	— —	Agree	Agree	Agree
Engine weight	Cruise $(T/W)_{POD}$ = 0.98	5% lower engine wt.	T/W_{POD} = 1.23	Agree
Nacelle	Separate flow fixed nozzle	Variable nozzle FPR < 1.4	Mixed flow	Variable nozzle BPR > 8
Performance data	SFC = 0.0188 kg/sec/kN = (0.662 lb/hr/lb)	Agree	Lower SFC	Agree
	F_N = 34 700 N (7800lb) at M = 0.8 = 9144m (30 000ft)	Agree	Higher thrust	Agree

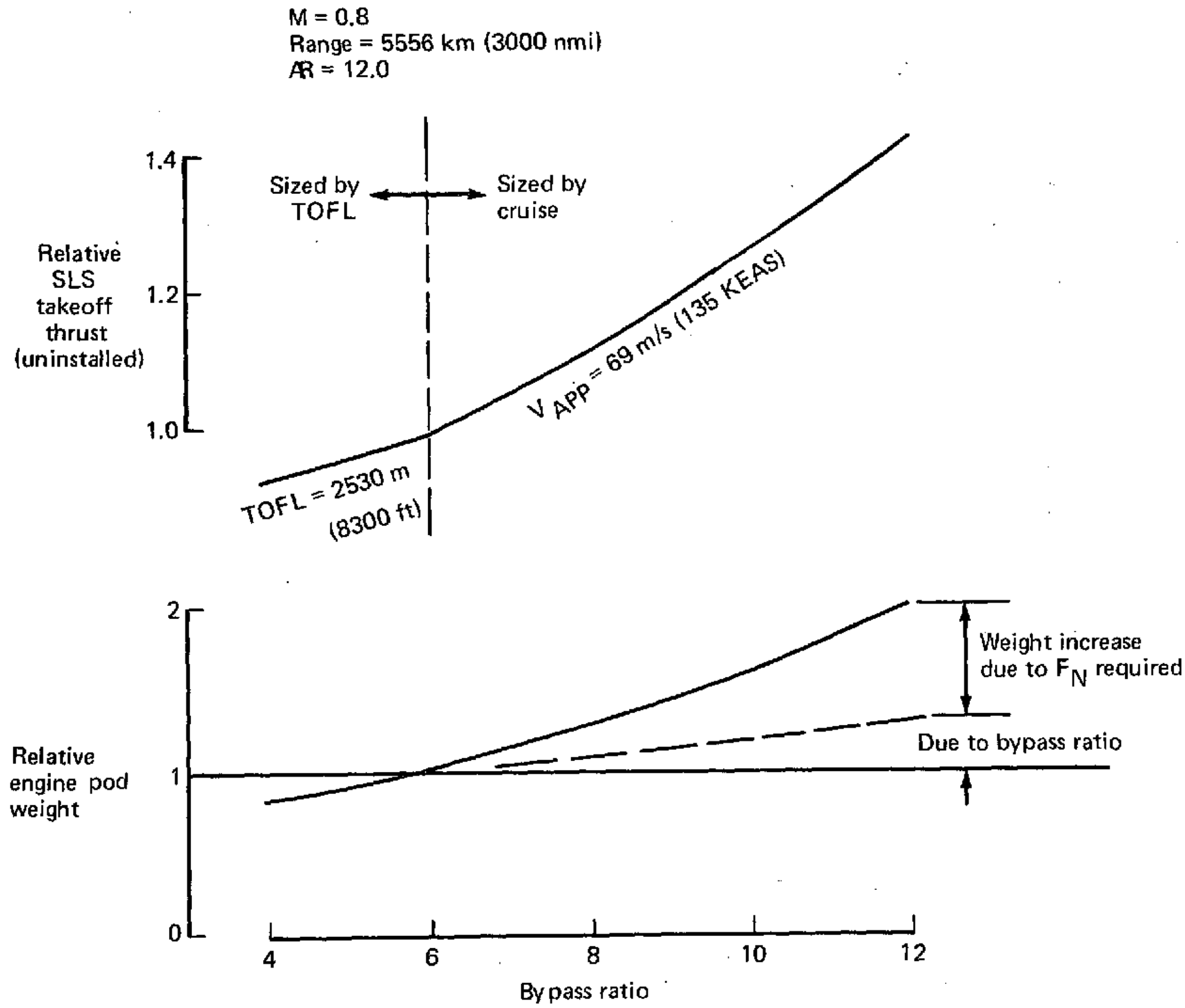


Figure 44.—Engine Weight Versus Bypass Ratio, Matched Airplane

Relative specific fuel consumption, cruise thrust at the average cruise altitude, and block fuel are shown in figure 45. Although SFC improves with higher BPR's, the thrust required also increases so that minimum block fuel occurs in the general range of BPR 6 to 8. The required cruise thrust increases because of increased gross weight and nacelle drag. The magnitude of the nacelle drag is indicated by the dashed line in figure 45. Nacelle drag alone nullifies the SFC benefits of high-bypass engines.

Fuel usage, DOC, and noise are summarized in figure 46. Direct operating cost, determined for a trip distance of 1850 km (1000 nmi), shows a more sharply defined minimum against BPR than fuel usage. The optimum BPR is 6. A doubling of the fuel price would not alter this conclusion. The 196-passenger aircraft configured with peripherally treated bypass-6 engines can achieve a traded noise level FAR 36 minus 5 EPNdB. Aircraft configured with

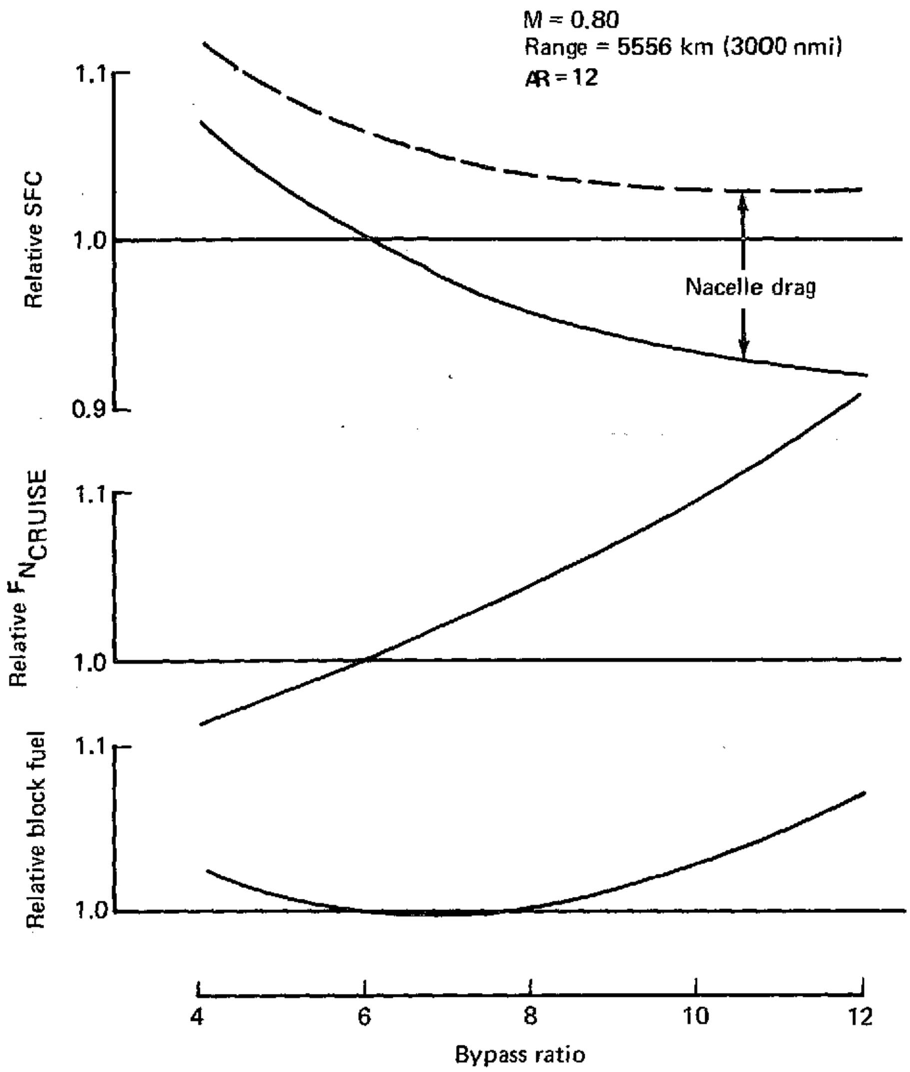


Figure 45.—Cruise SFC, Thrust and Block Fuel Versus Bypass Ratio

larger BPR engines will not improve the traded noise apreciably because traded noise is dominated by approach noise. Figure 47 shows the dominance of approach noise levels relative to takeoff and sideline noise. Takeoff noise levels with cutback and sideline noise are well below the approach noise levels.

4.4.3 UNCONVENTIONAL ENGINES

Although the basic study was conducted using the conventional turbofan cycle, it was desirable to determine the potential offered by alternate engine cycles. This section covers what should be considered as a preliminary analysis of three such cycles.

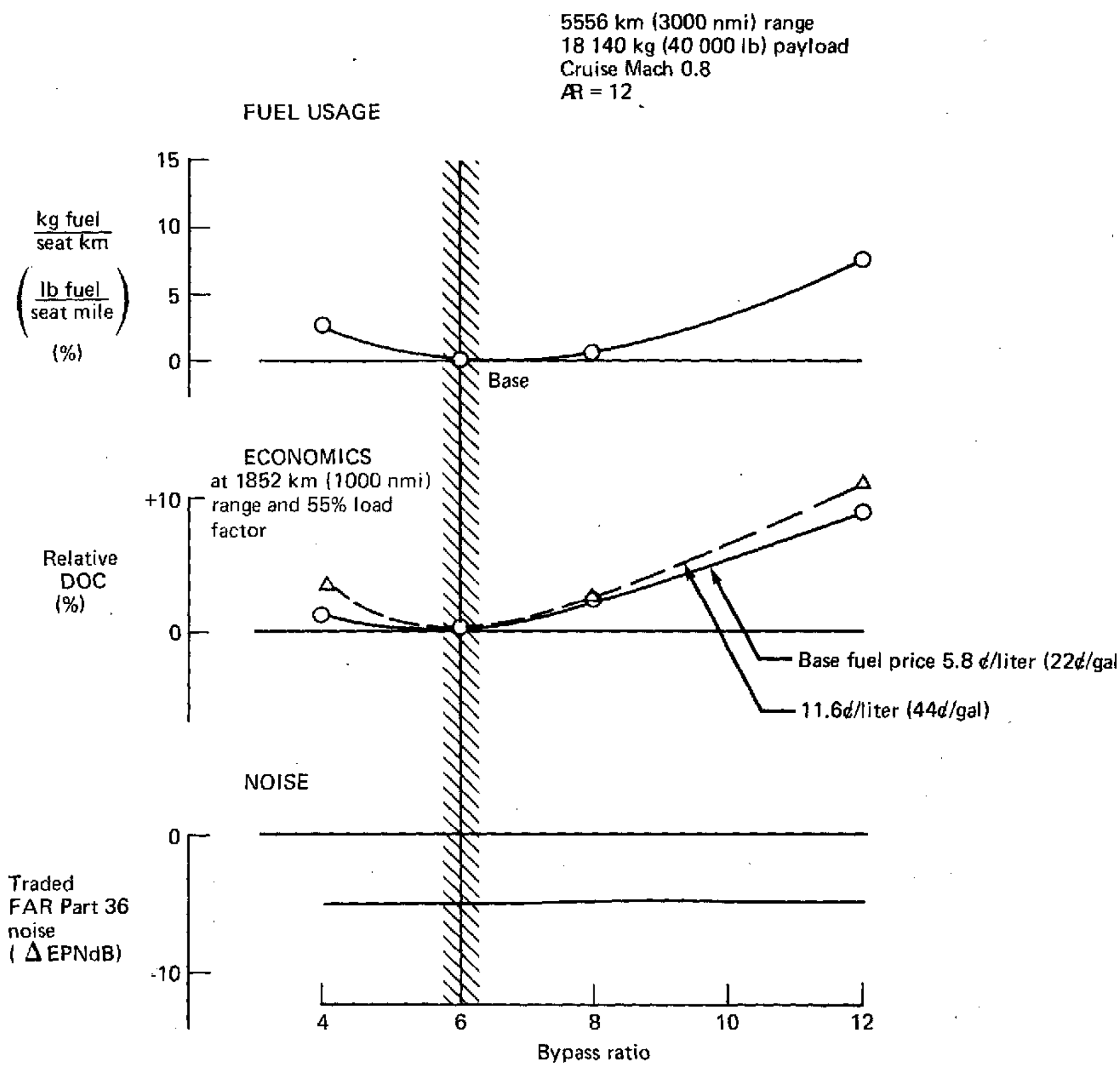


Figure 46.—Airplane Performance Summary

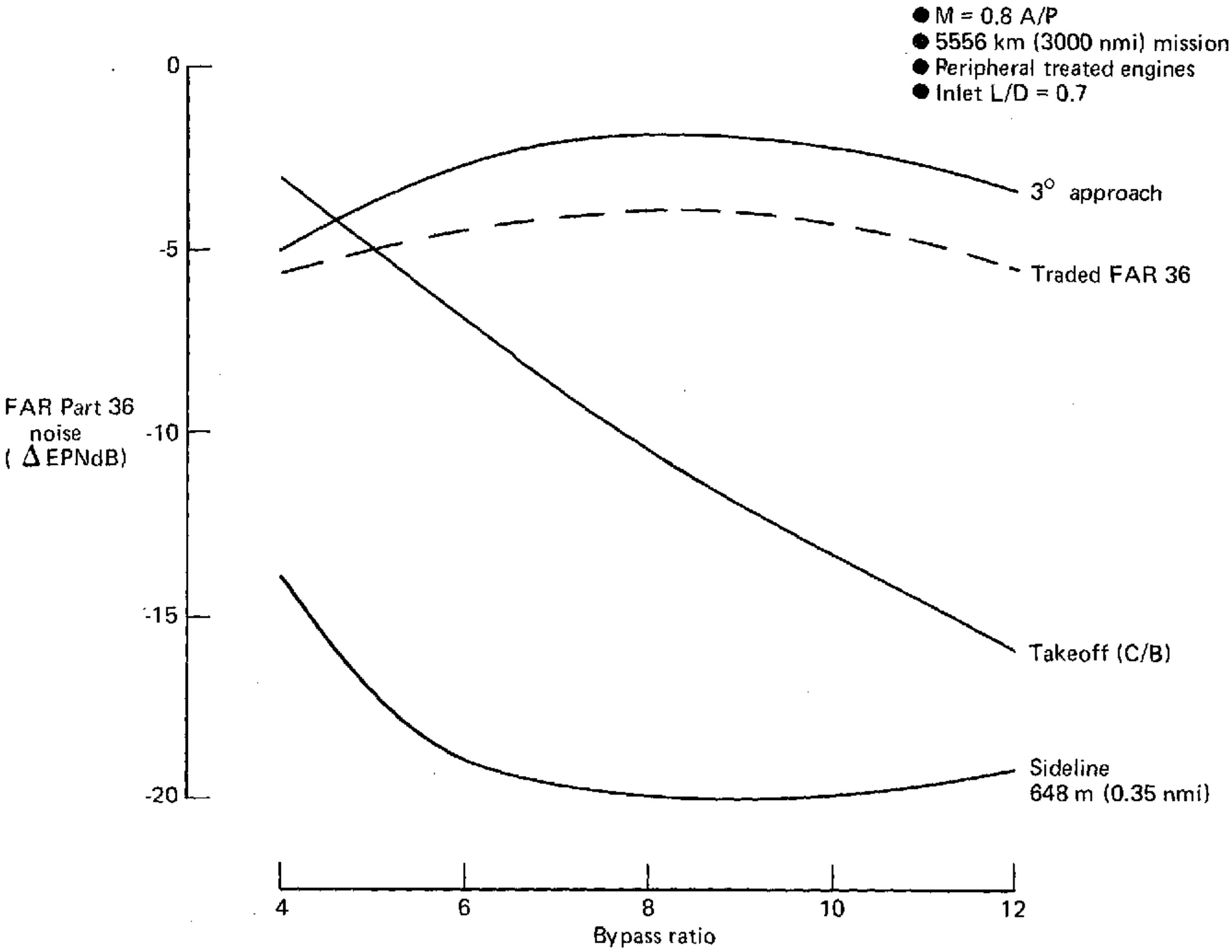


Figure 47.—Airplane Noise Versus Bypass Ratio, Conventional Engines

4.4.3.1 Technical Approach

The technical approach followed is shown in figure 48. The initial list of candidate engines included the multicycle engine, geared fan, regenerative fan or turboprop, advanced technology turboprop, variable-pitch turbofan, and the high OPR turbofan.

A preliminary investigation of the multicycle engine characteristics at a fixed subsonic cruise speed (M = 0.8) failed to show potential for fuel savings. This engine type appears best suited for missions where low fuel consumption is required at significantly different cruise speeds. Also, the geared fan was not considered unique but could be used in any case on those turbofans where it would improve the turbine/fan speed relationship.

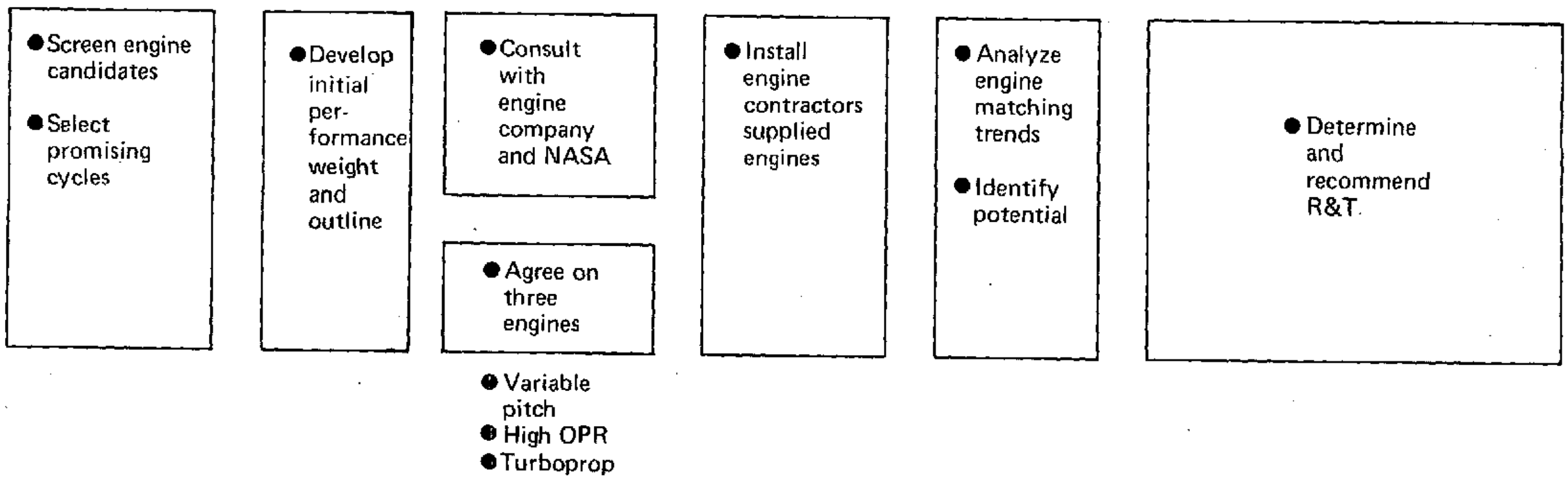


Figure 48.—Technical Approach, Unconventional Engines

Considerable work was done on regenerative cycles; however, in view of the installation difficulties (discussed later), a decision was made to concentrate on the advanced technology turboprop, the variable-pitch turbofan, and the high OPR turbofan for additional airplane studies. This decision was reached jointly by the contractor, P&WA, and NASA.

Engine data for these studies were provided by Pratt & Whitney Aircraft and were coordinated by the contractor. These data included estimated costs, dimensions, performance, and weights for each of the engines. A summary of these data is included in appendix A. The data were provided for engines of approximately the correct size. Scaling rules were applied in the airplane studies.

4.4.3.2 Regenerative Turbofans and Turboprops

Extensive studies were conducted to assess the potential of regeneration for current technology engines. Regeneration is not effective when used with cycles having compressor pressure ratios of 24, such as used in the BPR study. This is because the relatively small difference between compressor outlet temperature and the turbine outlet temperature does not permit sufficient heat transfer to effect a saving in fuel. Parametric regenerative cycle studies were performed, showing the optimum OPR to be approximately 10 for a turbine inlet temperature of 1420 K (2550° R) at cruise.

Initial studies showed that the heat exchanger must have an effectiveness of approximately 0.9 with a pressure loss of not more than 10% (total for both sides) in order to provide a reasonable potential for fuel savings. Airplane sensitivity studies showed that block fuel savings of 10% could be realized, provided the weight of the heat exchanger, ducting, and additional nacelle weight did not exceed 25% to 30% of the bare engine weight. No allowance was made for an increase in nacelle drag. The reduction in SFC of various engines types with regeneration is indicated in figure 49. For the BPR 6 at $M = 0.8$, the improvement in SFC is about 10%; for the turboprop at $M = 0.6$, the improvement is 11%.

The heat exchanger weight and dimensions are extremely critical items. Initial designs were based on conventional shell and tube construction. These were found to be totally inadequate from both weight and space standpoints. Plate fin and liquid-coupled heat exchangers were found to be smaller but excessively heavy.

The rotary-type heat exchanger with a ceramic matrix was then studied in some detail. This type of heat exchanger appears to offer the greatest potential for regenerative aircraft engines.

A series of rotary heat exchangers were designed to provide 0.90 effectiveness for a 6 to 1 BPR turbofan at $M = 0.8$ and 9144-m (30 000-ft) altitude at the maximum cruise thrust rating. The heat exchanger matrix was assumed to be Corning Glass Works "CERCOR" number T20-38. The output of this study defined the matrix weight, area perpendicular to the flow, and the passage flow length as functions of the total pressure drop through the core. There are many possible ways to arrange the heat exchanger. In this study, it was assumed to be a single rotating cylindrical drum located behind the last turbine stage, as indicated at the top of figure 50. The required envelope of the heat exchanger, associated

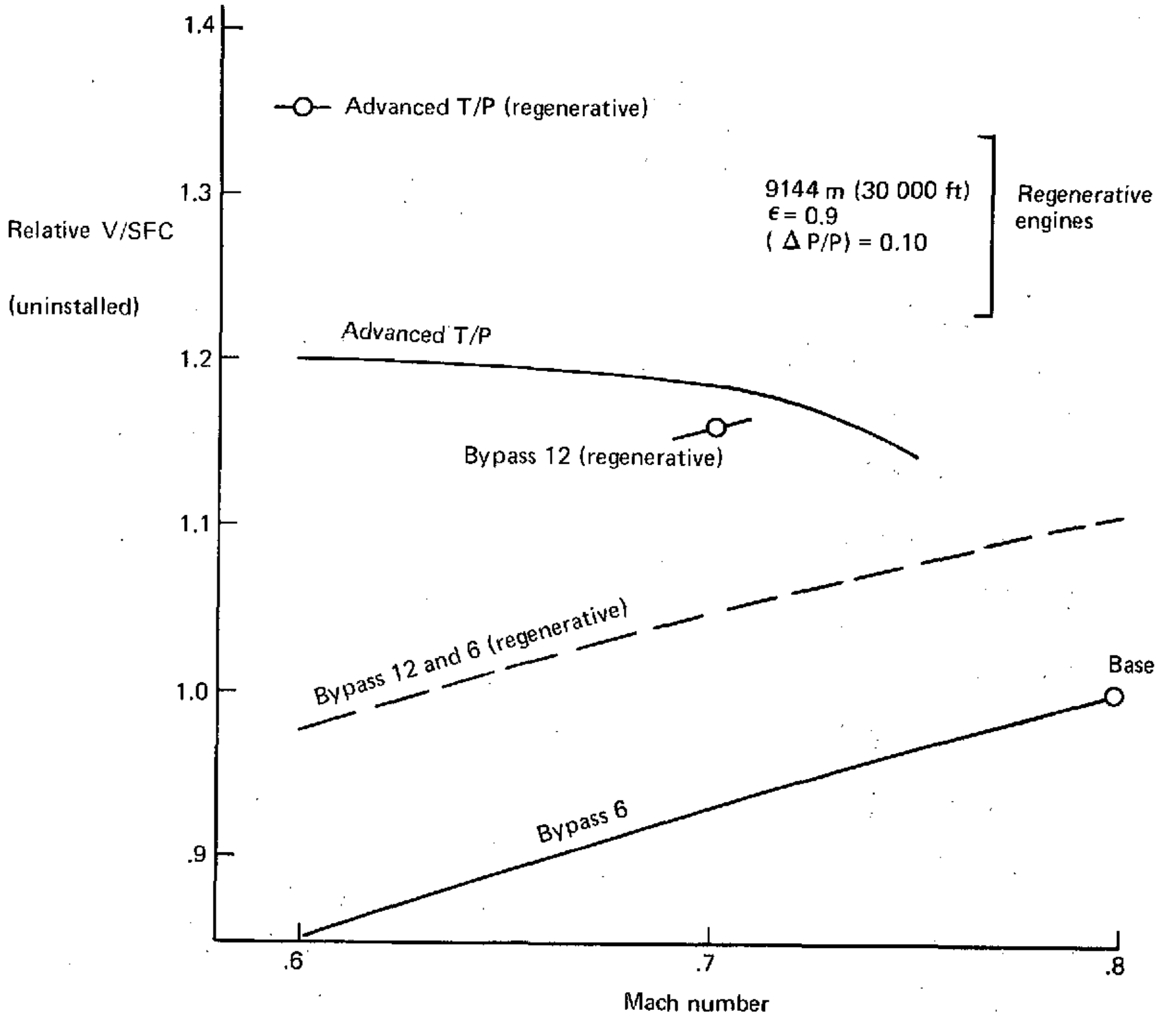


Figure 49.—Regenerative Engine V/SFC

ducting, and the matrix weight is shown at the bottom of the figure. The heat exchanger matrix weights are reasonable; however, the required length is about equal to the engine length, and some increase in nacelle diameter would be necessary. Although it was realized that the physical arrangement assumed probably was not optimum, the space requirement for the heat exchanger appeared so great that further work on regenerative cycles was discontinued.

4.4.3.3 Advanced-Technology Turboprop

Data for the turboshaft engine was provided by the engine subcontractor. These data are based on an engine with an overall pressure ratio of 20 to 1 and a maximum combustor exit temperature of 1590 K (2860° R). Cabin air requirements were assumed to be provided by an air engine-driven compressor, since the penalty for such airbleed from a turboprop is prohibitive. The total shaft-power extraction was 142 kW (190 hp) per engine.

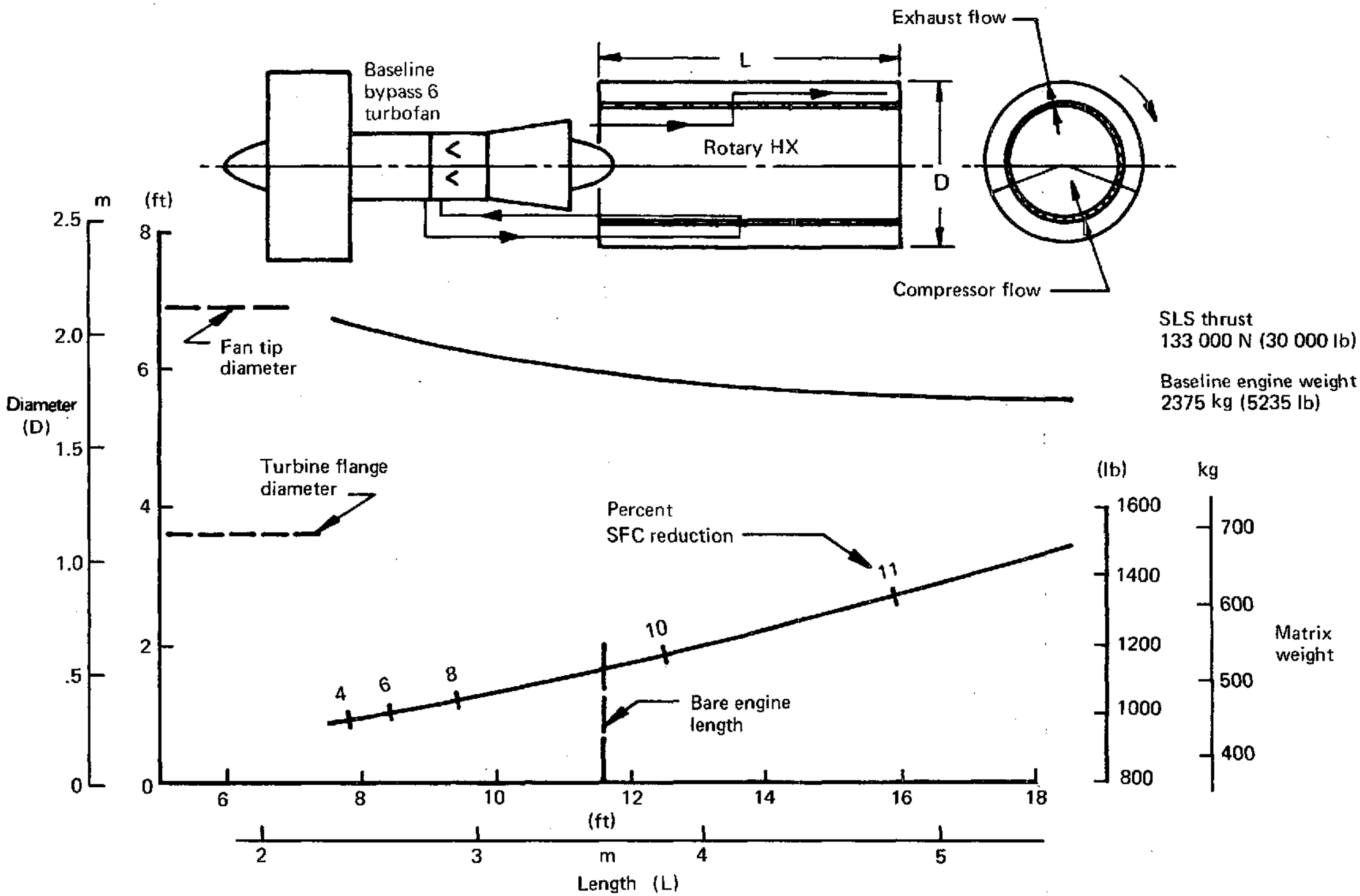


Figure 50.—Regenerative Turbofan Possible Heat Exchanger Envelope

The propeller was selected from data contained in reference 7. Propeller characteristics are as follows:

Diameter (for the sized airplane)	5.49 m (18.0 ft)
Number of blades	4
Tip speed, takeoff	244 m/s (800 ft/sec)
Tip speed, all other conditions	213 m/s (700 ft/sec)
Activity factor	140
Integrated lift coefficient	0.3

Performance characteristics of the turboprop engine are shown in section 4.4.3.6 together with the performance characteristics of the variable-pitch engine and the high OPR turbofan. An installation sketch showing the turboprop nacelle in the inboard wing position is shown in figure 51.

4.4.3.4 Variable-Pitch Turbofan

A fan pressure ratio of 1.4 at the maximum cruise design condition was selected, and the OPR and turbine temperature ratings were the same as for the conventional turbofans. The BPR was 8.4.

The variable-pitch fan is coupled to the low turbine through a gearbox and runs at lower tip speeds than the conventional fan. The fan is capable of reverse thrust operation, eliminating the need for the conventional blocker door and cascade-type fan thrust reverser. A three-position fan nozzle is used for takeoff, cruise, and reverse thrust operation.

An installation sketch showing the variable-pitch turbofan nacelle is shown in figure 52.

4.4.3.5 High Overall Pressure Ratio Turbofan

The advantages of compressor pressure ratios higher than those used for the conventional turbofans (24 to 1) cannot be realized unless turbine cooling air requirements can be reduced. Normally, pressure ratios higher than 24 result in an increase in the quantity of cooling air required sufficient to make SFC worse rather than better. One means of reducing the quantity of cooling air required is to cool the compressor discharge bleed air with fan air. Typical results of a Boeing study are shown in figure 53. Improved turbine blade materials, capable of operating at higher metal temperatures, would also reduce cooling air requirements.

The high OPR cycle supplied by the engine subcontractor had an OPR of 40 at a BPR of 6.4. For consistency, turbine inlet temperature ratings were the same as used for the conventional turbofans.

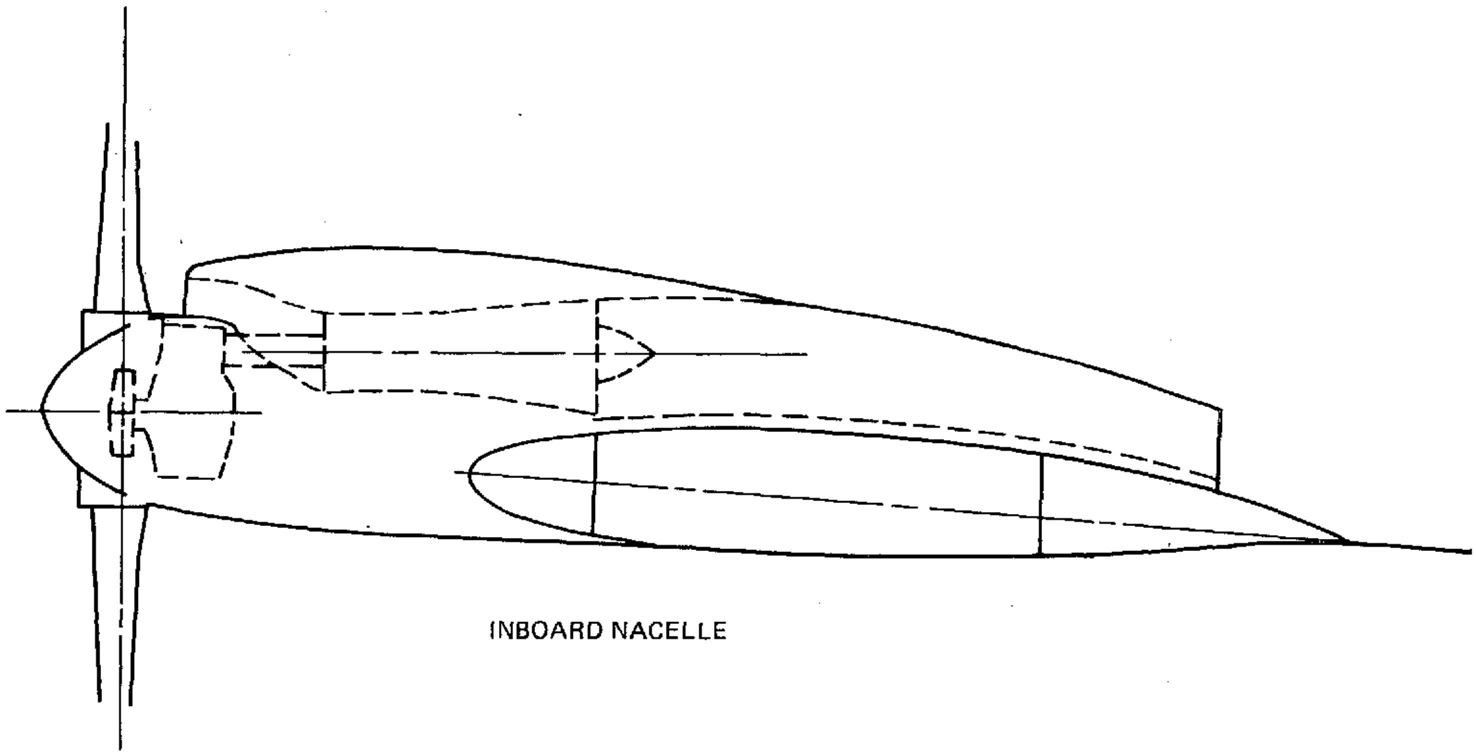


Figure 51.—Schematic of Advanced Turboprop Inboard Nacelle

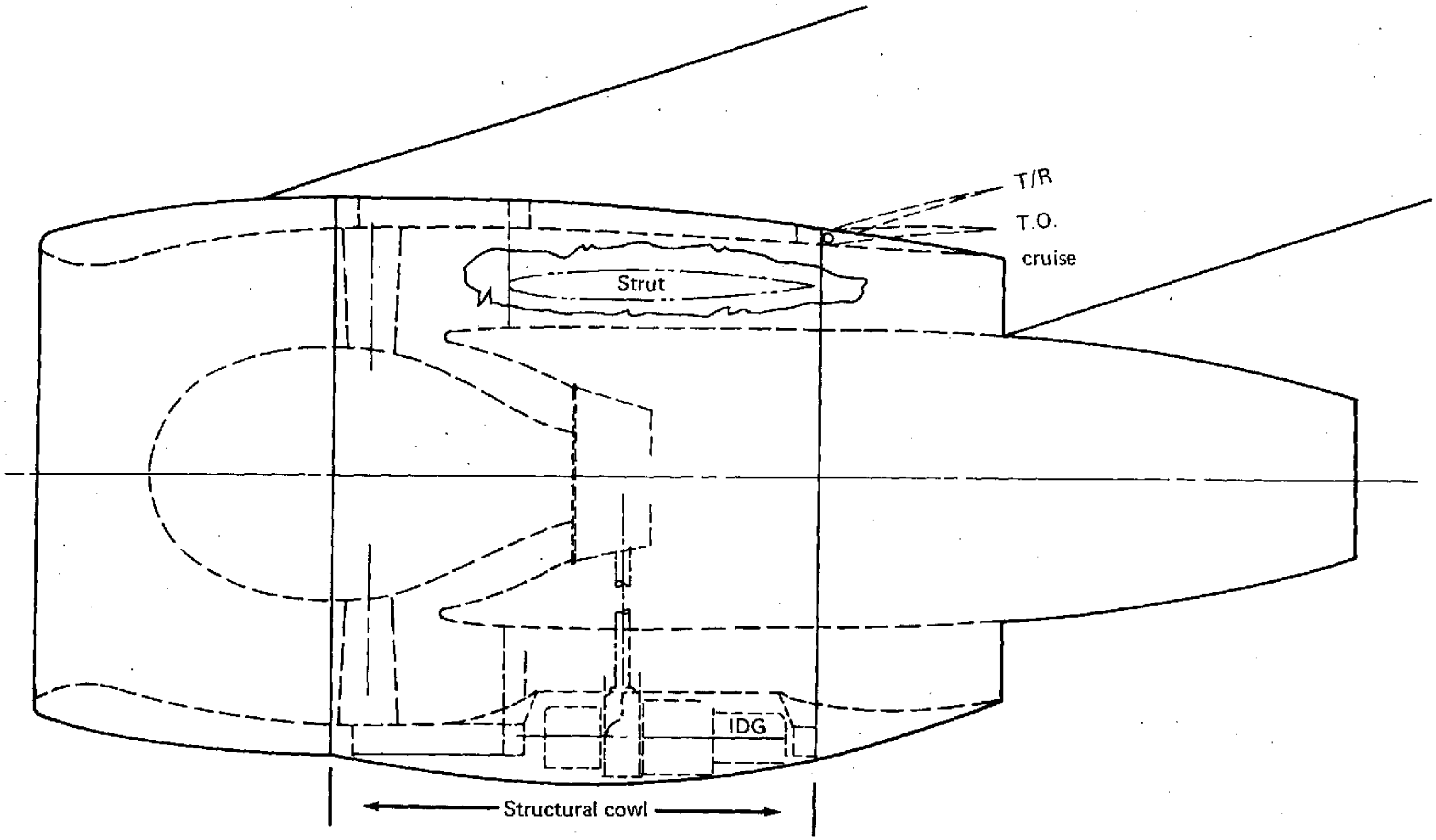


Figure 52.—Nacelle for Variable Pitch Turbofan

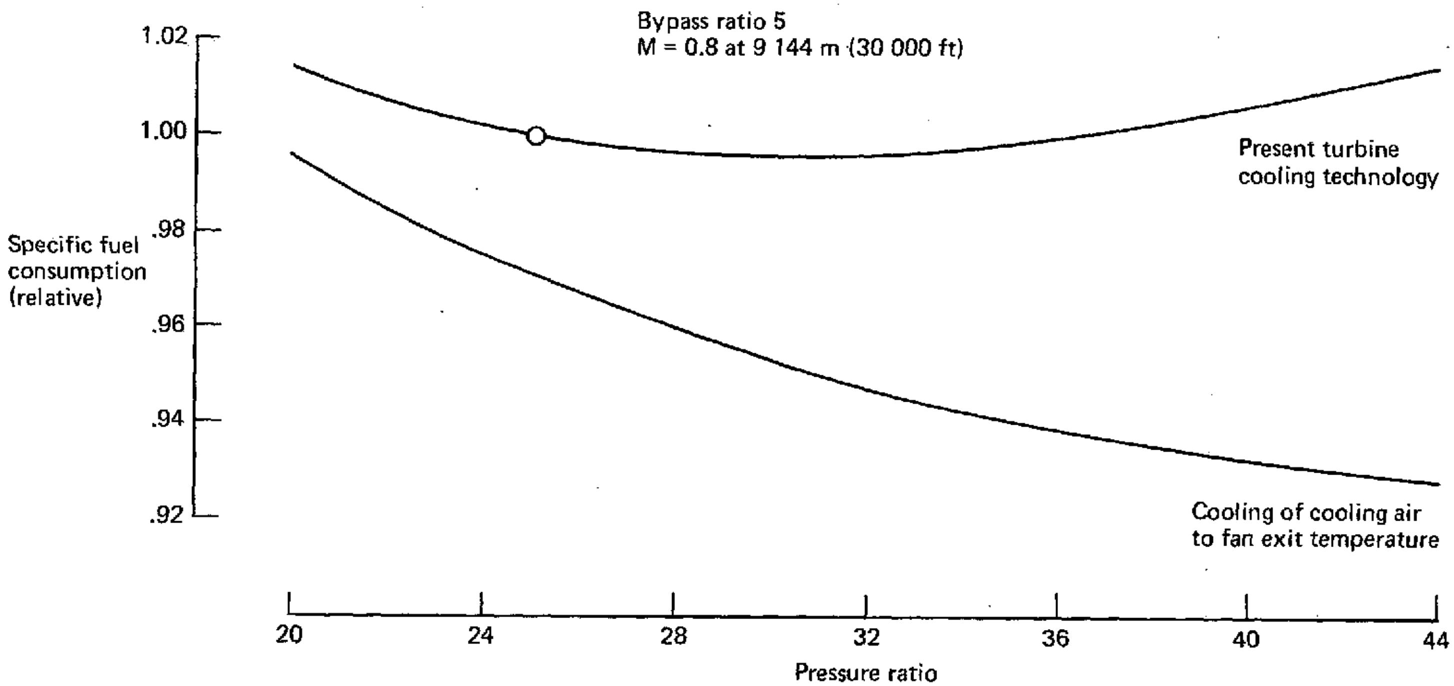


Figure 53.—Potential of High OPR Cycle

4.4.3.6 Performance Characteristics of the Unconventional Engines

Takeoff thrust as a function of airspeed is shown in figure 54. The value of takeoff thrust for each of the engines is normalized to have a value of unity at zero speed. None of the unconventional engines were sized by the maximum allowable TOFL requirement of 2430 m (8300 ft).

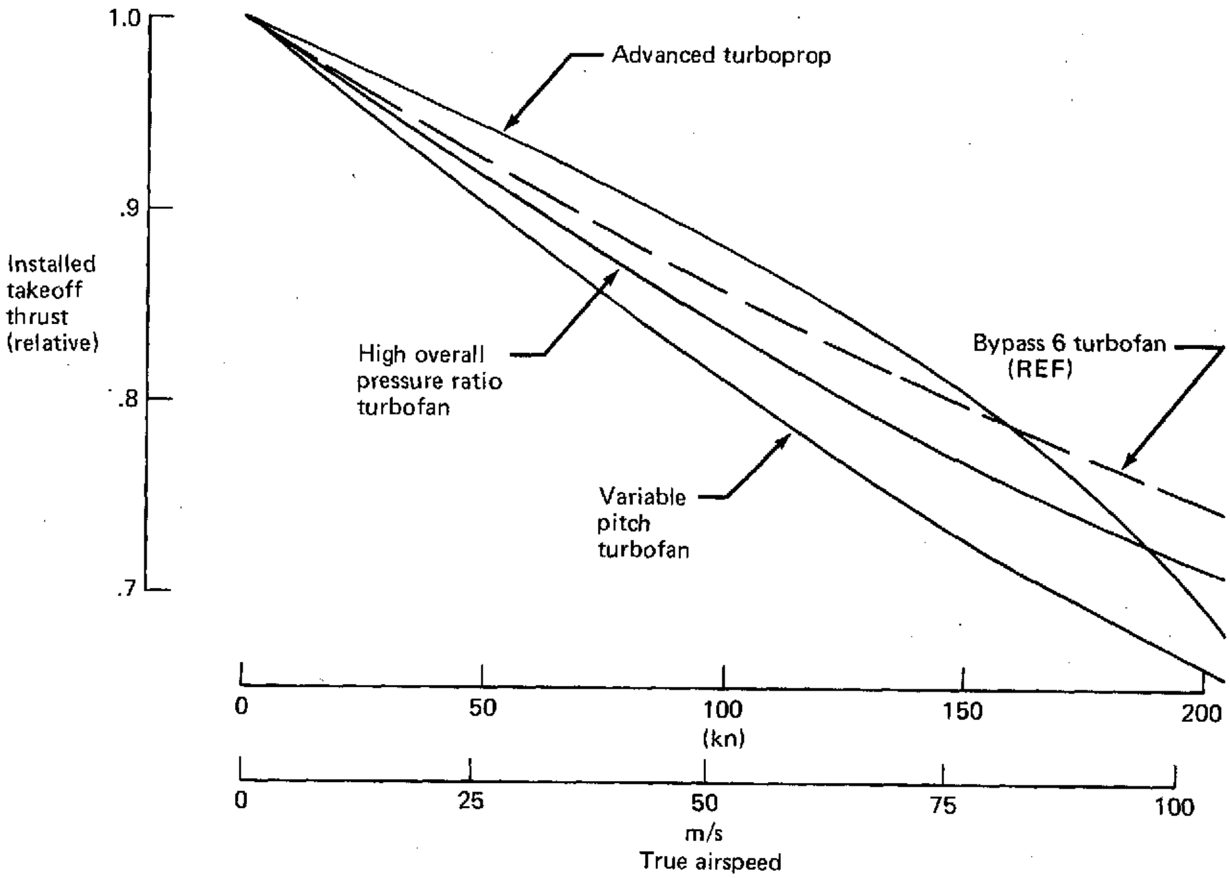


Figure 54—Takeoff Thrust Versus Airspeed, Unconventional Engines

The lapse rate or the ratio of cruise to takeoff thrust for each of the engines is shown in figure 55. Since all of the engines were sized by the cruise thrust requirement, the lapse rate and the cruise thrust required determine the thrust available for takeoff. The basis for selection of the initial cruise altitude is discussed in section 4.4.3.7.

Installed cruise thrust per unit pod weight is shown in figure 56. Pod weight includes the bare engine weight, the nacelle weight, and the reverser weight (if applicable). A minimum initial cruise altitude of 9144 m (30 000 ft) was used for all airplane studies in order to avoid most adverse weather conditions. For the advanced turboprop, design initial cruise altitudes higher than 30 000 feet required an increase in block fuel. Thus, the minimum

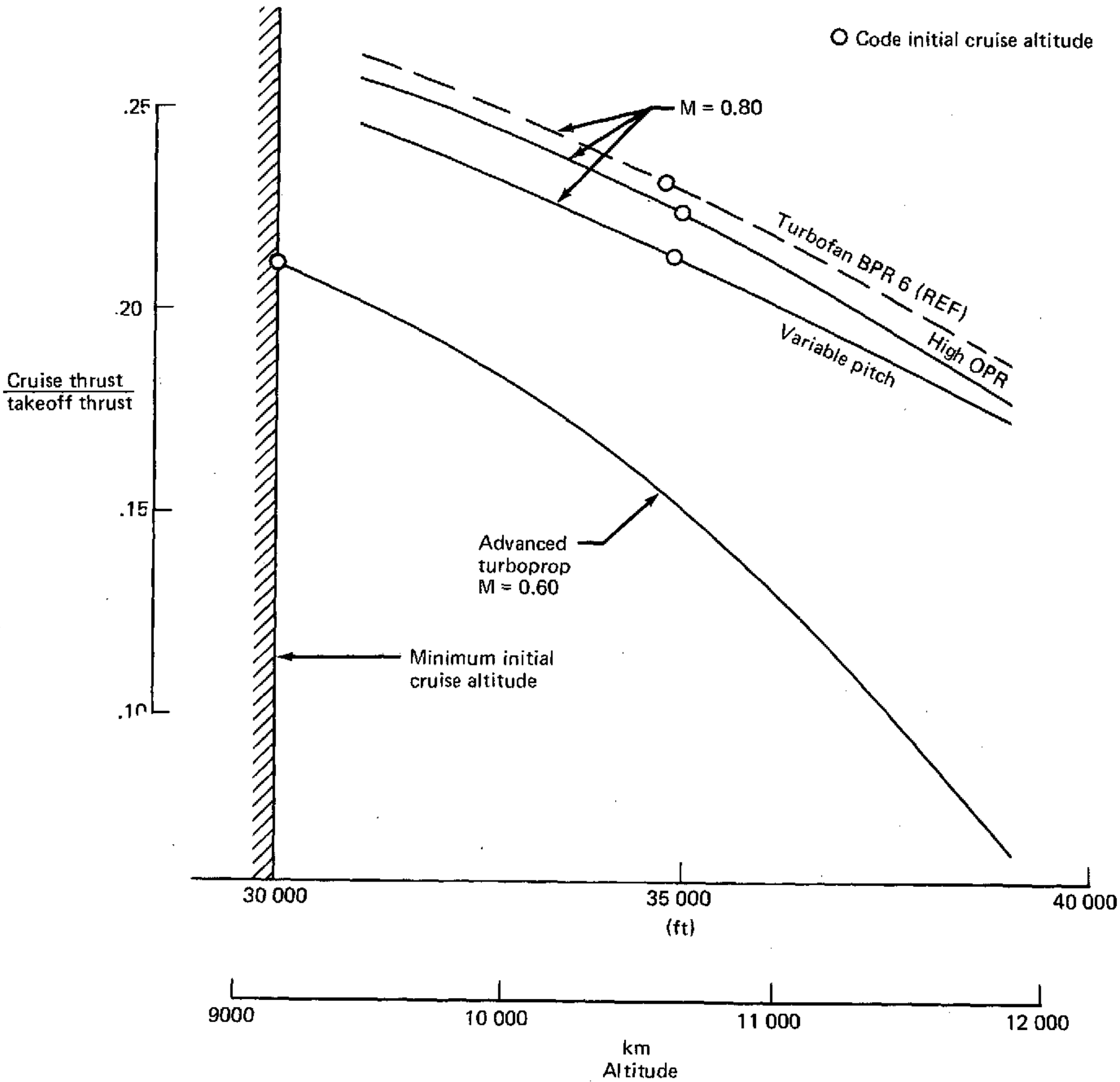


Figure 55.—Lapse Rate Unconventional Engines

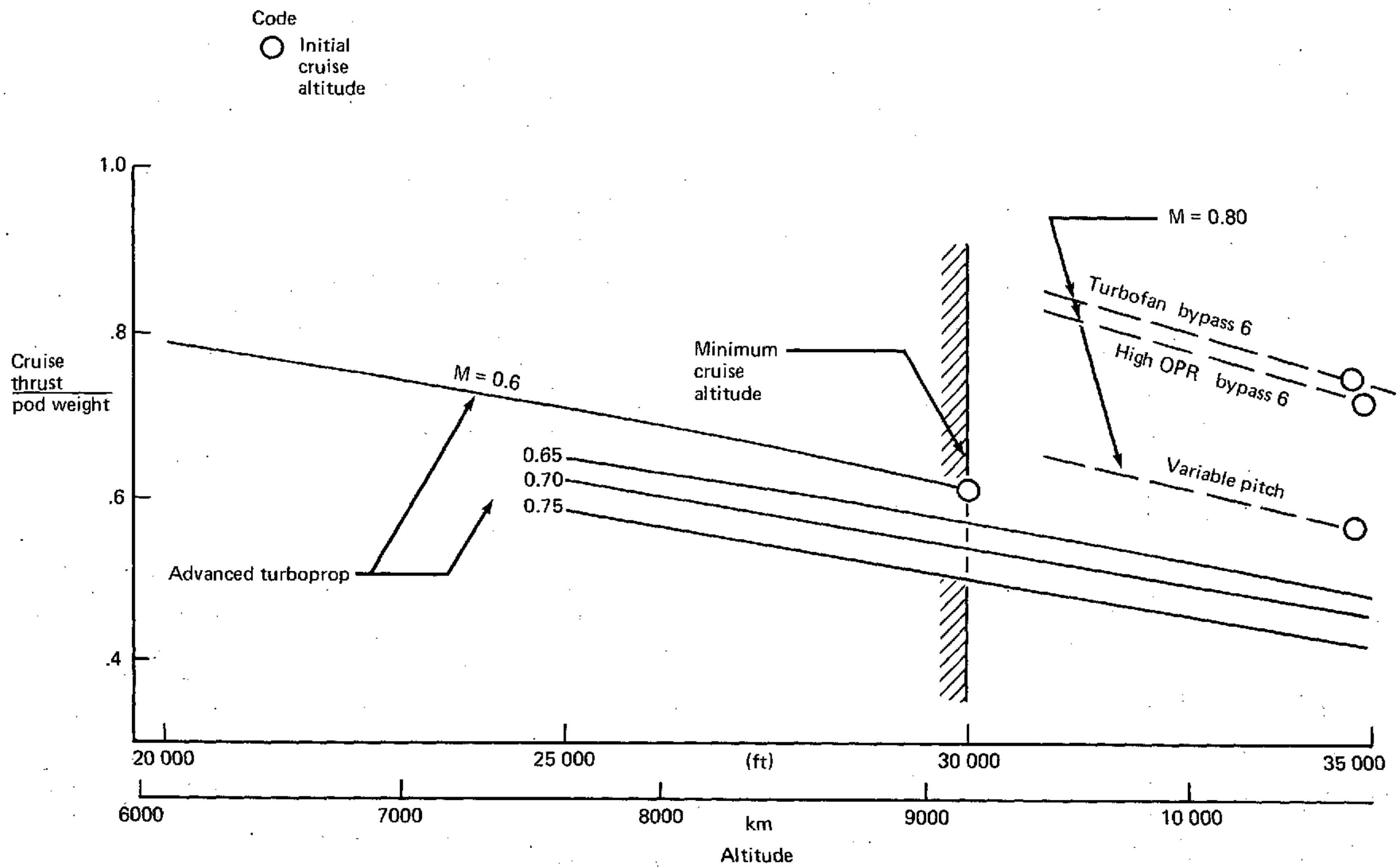


Figure 56.—Propulsion System Weight Considerations

initial cruise altitude was that for minimum block fuel for the advanced turboprop. The high OPR and variable-pitch turbofans were found to require an initial cruise altitude of approximately 10 670 m (35 000 ft) for minimum block fuel.

The value of cruise SFC (plotted as V/SFC) for each of the unconventional engines is superimposed on the conventional turbofan study engine data in figure 57. The advanced turboprop shows a significant potential for fuel savings at M = 0.6 and 0.7. The SFC of the variable-pitch engine is only about 2% better than the conventional BPR-6 turbofan because of the relatively low fan pressure ratio.

4.4.3.7 Results of Airplane Studies With Unconventional Engines

Engine scaling rules for dimensions, weights, and performance were established for the airplane studies. Engine bleed air allowances for the variable-pitch turbofan and the high OPR turbofan were the same as used for the BPR study. For the advanced turboprop, cabin air requirements were assumed to be provided by an engine-driven compressor with a total shaft-power extraction (including that required for airplane electrical and hydraulic systems) of 142 kW (190 hp) per engine.

The airplanes with the variable-pitch engine and the high OPR turbofan were designed for a cruise Mach number of 0.8, an AR of 12, and a sweep of 30°. The advanced turboprop airplane had a design cruise speed of M = 0.6, an AR of 10, and 7° of sweep. The turboprop airplane was designed prior to completion of the planform study, and at that time the advantages of AR 12 relative to AR 10 had not been identified. The effect of this difference in aspect ratio is subsequently accounted for in fuel usage and economic studies.

Relative takeoff thrust for each of the matched airplanes is shown on the upper portion of figure 58. Although the advanced turboprop has relatively low takeoff thrust, the takeoff field length, 1707 m (5600 ft), is less than the maximum permitted. The other concepts met the 2430-m (8300-ft) field length requirement with selected flap settings. As stated earlier, all of the unconventional engines were sized by the cruise thrust requirement. The takeoff thrust of all of the engines primarily reflects the start of cruise weight as suggested by table 8, and biased by the lapse rate of the various engines (fig. 55).

The relative pod weights (engine, nacelle, and thrust reverser, if required) are shown in the lower portion of figure 58. The high OPR engine falls on the BPR study line because the specific engine weight (thrust/engine weight) is essentially the same as a conventional turbofan. The pod for the variable-pitch engine is slightly heavier than a fixed-pitch engine of equal BPR. This is because the relatively low fan pressure ratio results in lower thrust per unit airflow, and a larger engine size is necessary. Increased engine and nacelle weight is greater than the weight saved by not requiring a thrust reverser. Pod weight of the variable-pitch engine is 40% greater than the conventional BPR-6 turbofan. Pod weight of the advanced turboprop is about 15% greater than the conventional BPR-6 turbofan despite the fact that the takeoff thrust available is about 6% less.

Fuel usage, economics, and noise for the unconventional engines are compared with the conventional BPR-6 turbofan in figure 59. In order to obtain correct incremental fuel usage

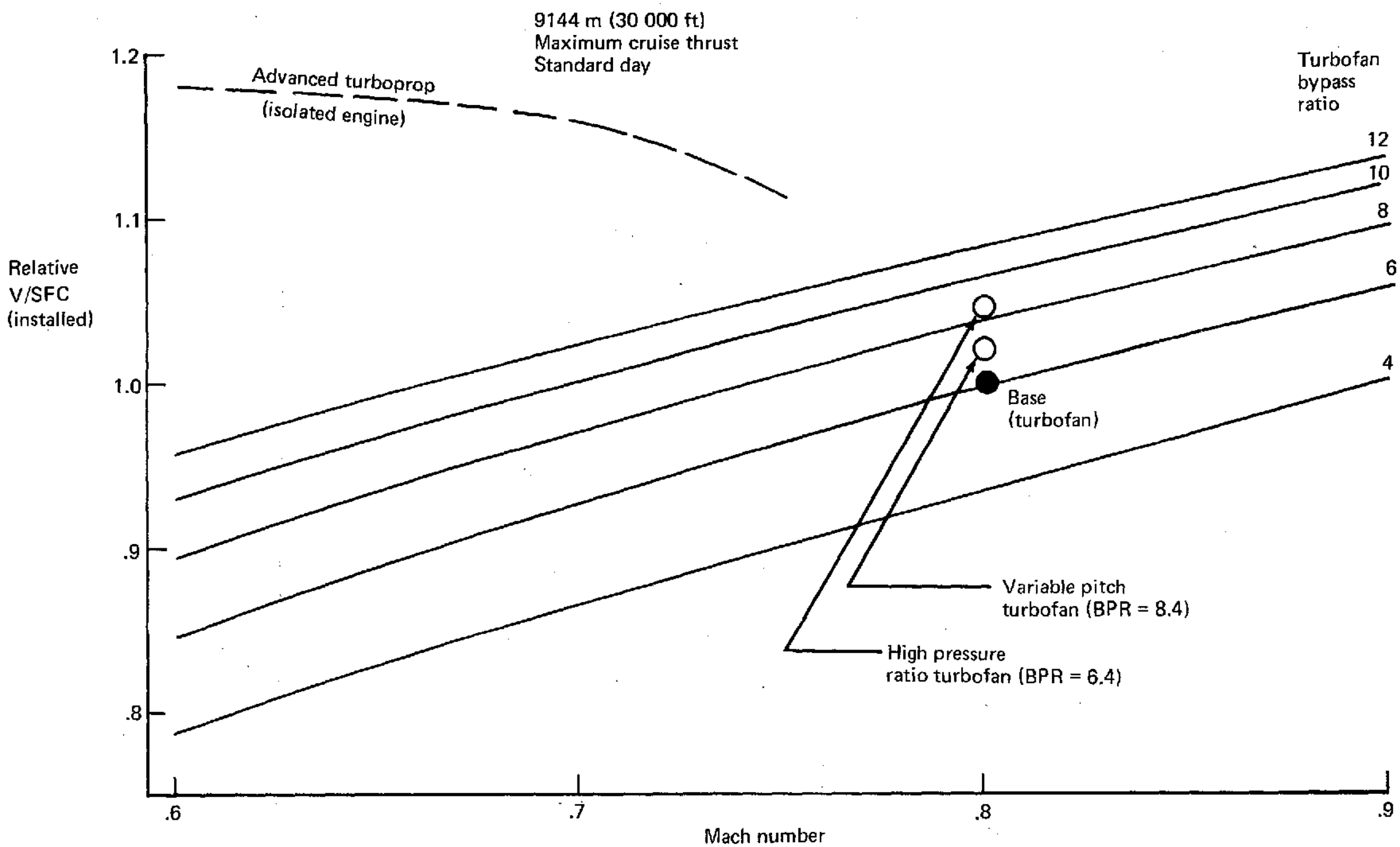


Figure 57.—V/SFC Versus Bypass Ratio, Unconventional Engines

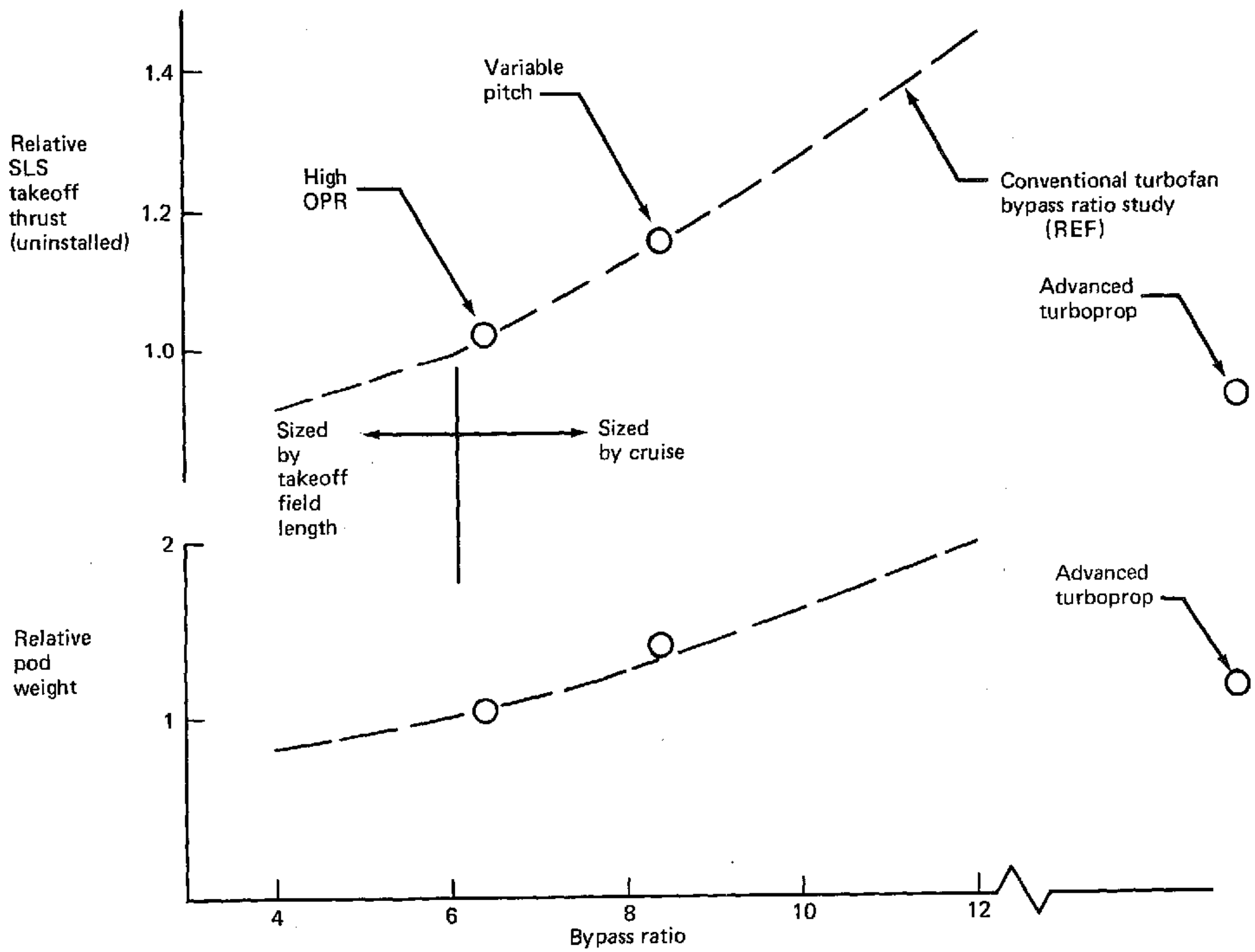


Figure 58.—Takeoff Thrust and Pod Weight, Unconventional Engines

Table 8.—Unconventional Engines Trade Study Results

Relative Values	Conventional Turbofan BPR 6	Advanced Turboprop	Variable Pitch Turbofan	High OPR Turbofan
TOGW	1.0	0.91	1.05	0.99
OEW	1.0	0.95	1.07	1.00

and economics, the advanced turboprop is shown relative to an AR-10 airplane with conventional turbofans.

The fuel usage of the variable-pitch engine is about 4% higher than the reference engine, primarily because the small SFC improvement (2%) is not sufficient to balance the increase in TOGW associated with the greater pod weight of the variable-pitch engine. Since the SFC improvement of the variable-pitch engine was small, a side study was conducted of an alternate variable-pitch engine having the same pressure ratio but with a BPR of 10.8. This provided an additional improvement in SFC of 4.5%; however, no saving in fuel usage was realized because of the further increase in pod weight.

Fuel usage was reduced about 3% with the high OPR cycle. This is consistent with the SFC improvement of 4% and the fact that this engine is about equal to the BPR-6 turbofan with respect to pod weight and size. The advanced turboprop reduced fuel usage 24%. To achieve this improvement on a fuel per passenger basis, the turboprop airplane would have to achieve the same load factor as the conventional BPR-6 turbofan despite the substantial speed difference.

Aircraft using unconventional engines showed higher operating cost than similar aircraft with conventional engines in all cases. The variable-pitch engine did not show an improvement in fuel burn. Penalties were estimated in the area of pod weight, leading to high aircraft gross weight in the aircraft sized for this engine. The complexity of the engine was estimated to cause a 3% increase in engine price over that of a conventional engine with the same thrust.

Engine price (probably the most sensitive of the variables related to engines) of the high pressure ratio engine is estimated to be 21% greater than the price of a conventional engine of the same thrust. This penalty cannot be economically offset by the small (3%) improvement in fuel consumption. Weights are essentially equal when aircraft with high pressure ratio engines are compared with conventional engines.

Turboprop engines were also evaluated economically. Operating costs were estimated to be significantly higher for aircraft equipped with these engines when compared to similar aircraft equipped with turbofan engines. The reduced fuel consumption is more than offset by the increased block time for cruise at M = 0.6 on a 1852-km (1000-nmi) mission, the average mission for a 5556-km (3000-nmi) airplane. The fewer trips per year, additional crew pay, and additional airframe and engine maintenance (the portion that is a function of

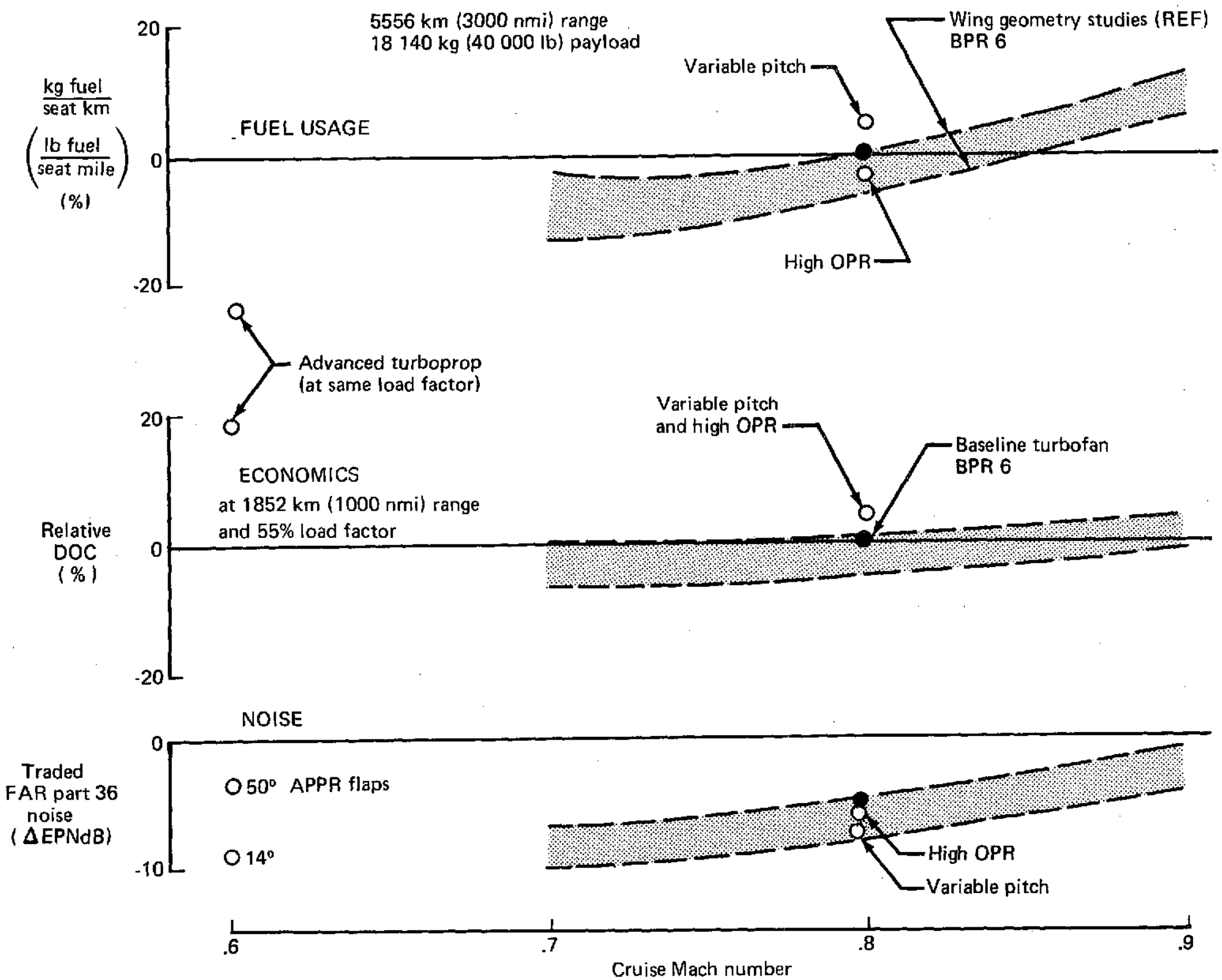


Figure 59.—Airplane Performance Summary

flight time) cost appreciably more than the cost of the fuel saved, provided fuel is priced at any reasonable level.

The noise for the low energy, peripherally treated, advanced engines is shown to fall in the shaded band of the conventional bypass-6 engine airplanes (with different flaps) at M = 0.8. The turboprop with a 14° flap configuration is shown to result in very quiet operations. (More flap would lead to substantially higher approach thrusts and noise and higher FAR 36 traded noise.)

A noise comparison of the three advanced engines with the conventional bypass-6 engine is shown in figure 60. The airplane sideline noise is shown to be very quiet (19 to 30 EPNdB, less than FAR 36). The approach noise for the turboprop with the 14° flap configuration is very quiet. The unchoked variable-pitch engine is several EPNdB quieter than the conventional bypass-6 engine at approach due to lower fan pressure ratio. At takeoff all engines are equally quiet. On a 3 to 2 traded-noise basis, small improvements in noise are made with each advanced engine ranging from FAR 36-5 to FAR 36-9.

4.4.4 ENGINE CYCLE STUDY CONCLUSIONS

The results of the engine cycle studies provided the basis for the following conclusions:

1. A BPR-6 conventional turbofan cycle should be used to define a candidate transport during the remainder of the study.

2. All three unconventional cycles should be subjected to a more detailed analysis by engine contractors than was permitted by this study. Such studies should be supported with evaluation by airframe contractors to establish characteristics, when considered on an installed basis, in a projected airline operational environment.

4.5 SECONDARY POWER SYSTEMS (SPS)

The secondary power systems include those systems that supply power for all airplane functions other than propulsion. These include the airplane hydraulic, electric, and pneumatic systems, and the auxiliary power unit (APU). The objective of the study was to examine the systems' power sources and their utilization to determine if there were potential for significant energy savings in the secondary power systems. The approach used was to determine relative fuel consumption to provide power, the required energy level, and alternate approaches to lessen the energy demand.

4.5.1 POTENTIAL FUEL SAVINGS OF SPS

The SPS studies were conducted for a 5556-km (3000-nmi), 196-passenger airplane with a Mach 0.8 cruise speed. An engine BPR of 6 was selected as being representative of the nominal.

Typically, the SPS uses about 5.7% of the total airplane fuel to supply the required power levels needed by the various airplane functions. This does not include fuel required to overcome system weight and drag penalties. Of the 5.7% fuel used by the SPS, about 22% is

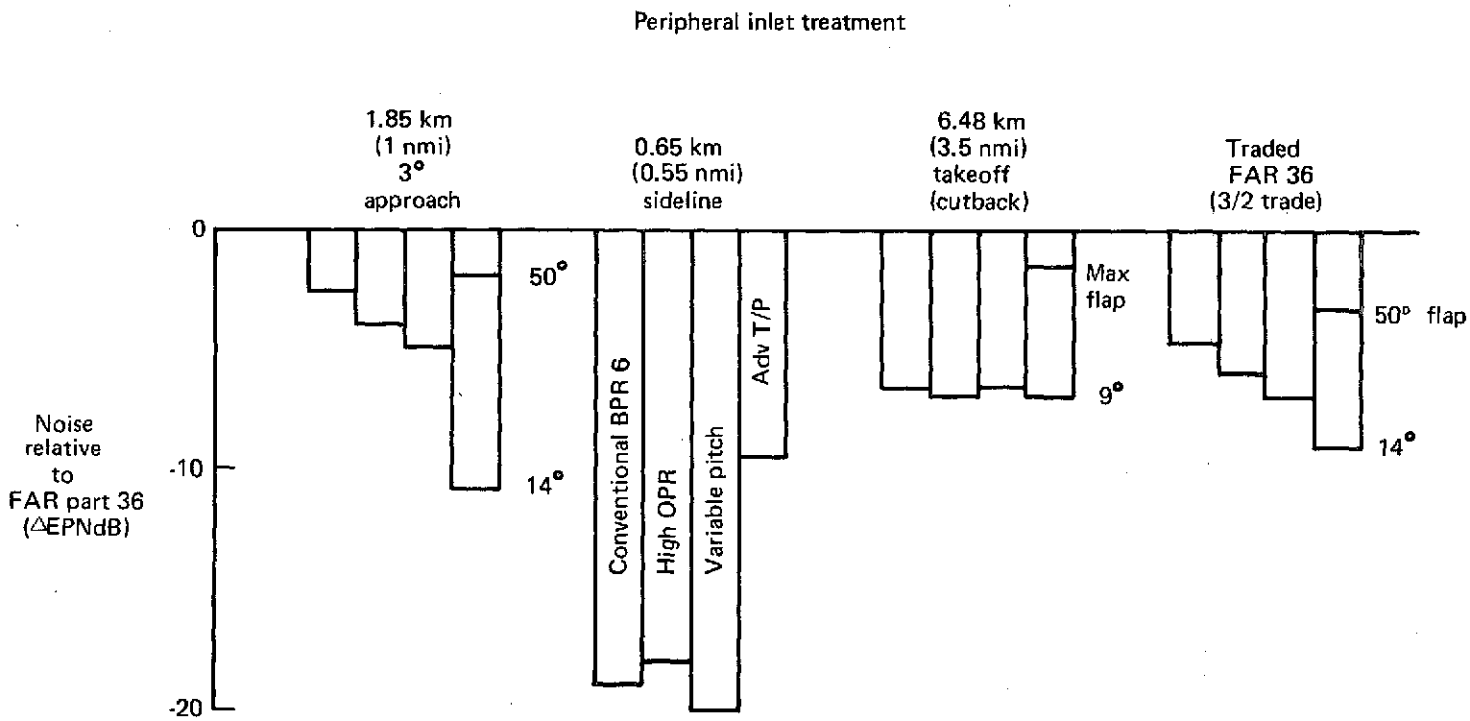


Figure 60.—Advanced Engine Noise Comparison

chargeable to the hydraulic and electrical systems. The larger share, 78%, goes to provide the pneumatic power requirements. The relative power extraction levels and losses for each power system are shown in figure 61.

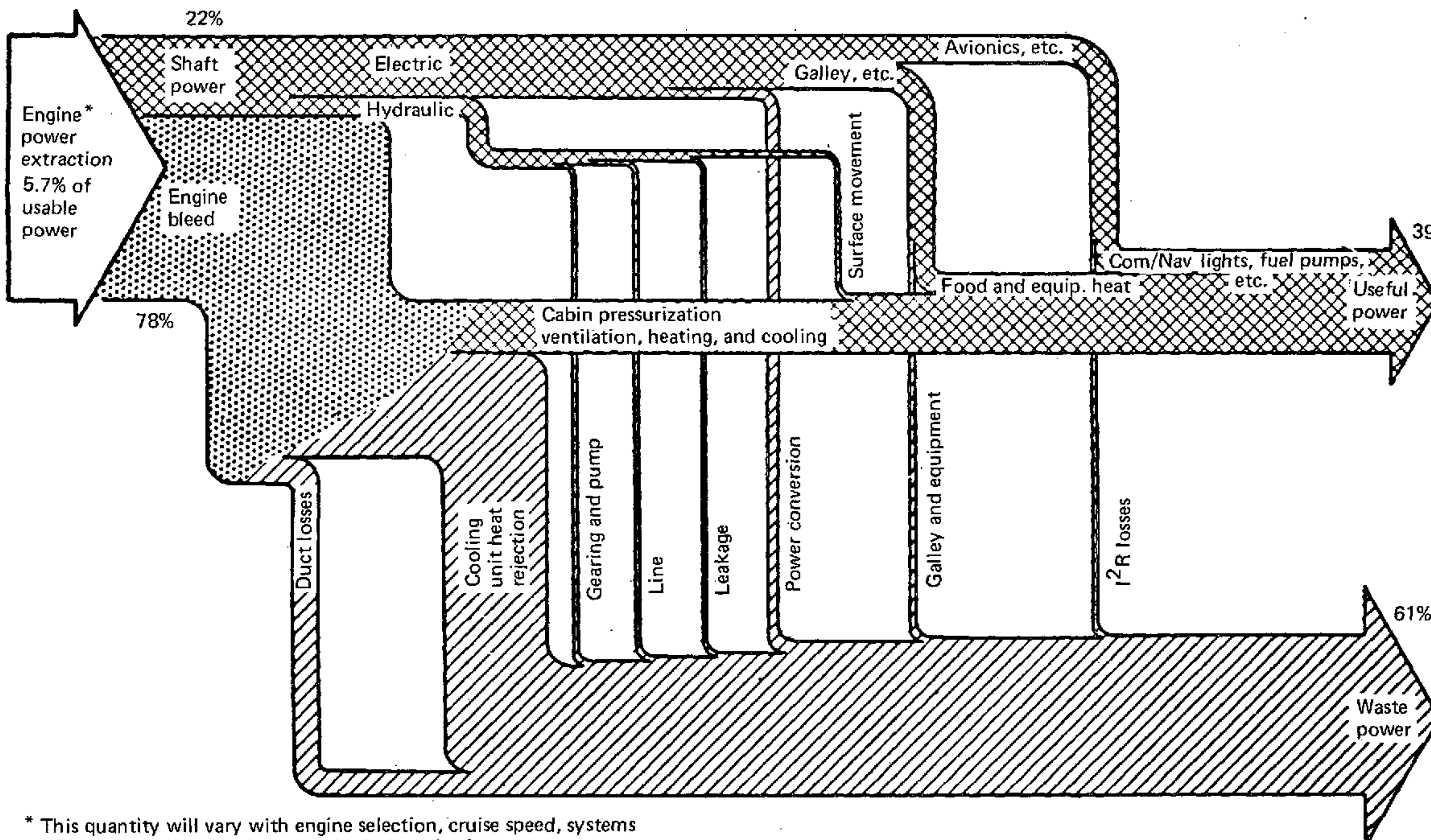
The electric and hydraulic systems shaft-power levels are necessary to perform specific airplane functions and to overcome relatively small energy conversion losses. The energy supplied to the airplane by these systems is in the form needed or is the most efficient means to provide the required function (e.g., electrical power for avionics, lights, galleys, and the high force capability of hydraulic power for surface control, brakes, and landing-gear actuation). Significant reductions in energy level of these two systems does not appear feasible unless the airplane operating functions, dispatch capability, and customer services are redefined to allow simpler, lighter weight, lower power systems. Also, the nominal power level extracted by present hydraulic and electric systems is relatively low. Thus, significant fuel savings are not available through improved power conversion techniques.

4.5.2 PNEUMATIC SYSTEM ANALYSIS

The pneumatic system is by far the largest power-using system and has the largest potential for energy usage reduction. Therefore, in this system, fuel savings areas were identified and studies conducted to identify possible fuel reduction levels. The relative costs of power to the various systems are shown in figure 62.

Secondary power systems penalties resolve to changes in engine thrust, specific fuel consumption, and airplane drag and weight. The sensitivities of the study airplane to incremental changes in these items are shown in figure 63. The relative costs of engine shaft power and engine compressor bleed air were determined from applicable engine data. These data show that for essentially equivalent power, engine bleed is about two and one-half times as costly as engine shaft power. The incremental penalties shown include the effects of resizing the airplane and engines to provide a configuration that will meet a specific payload/range condition. When the wing size, engine thrust, and TOGW for a particular airplane are fixed, the trade sensitivity factors must be modified to reflect operational increments (e.g., range, takeoff field length, cruise altitude, speed, and payload). Typical resulting factors are shown in table 9. These figures show that advantages to be gained by system modifications become significantly less when the airplane cannot be recycled. Therefore, major system modifications using new technology must be established as feasible prior to fixing the airplane design. The overall effects of resizing the airplane based on changes in the secondary power system are illustrated in figure 64. A 1.9% change to the airplane fuel consumption through a modified air-conditioning system resolves to a 3.5% change through the airplane resizing process.

The pneumatic power systems of modern jet transport aircraft use airplane engine compressor bleed air to provide engine inlet and wing thermal anti-icing, cabin air-conditioning, and drive power for selected secondary power system elements. This study assumed that the design loads except for cabin air conditioning would be handled by engine bleed. The main effort was made to identify potential savings that might be realized through modification of the large continuous air-conditioning system load. Approaches considered include replacing engine bleed air by boosting ram air in a separate shaft-driven compressor



* This quantity will vary with engine selection, cruise speed, systems configurations, airplane design, and other similar factors.

Figure 61.—Secondary Power System Energy Diagram, Typical Subsonic Cruise Mach 0.8 Transport

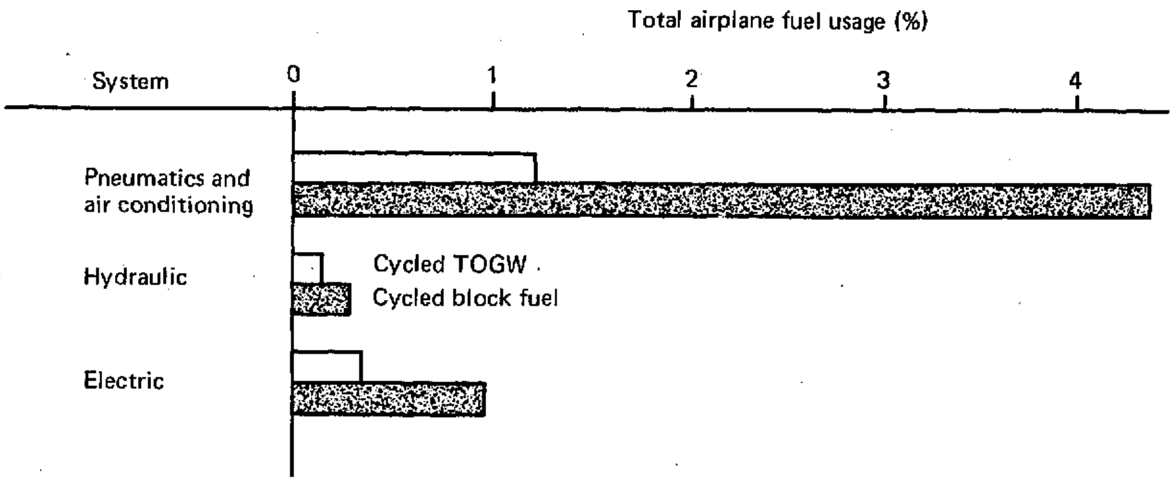


Figure 62.—Total Secondary Power System Fuel Usage Rate During Cruise

and reducing the fresh air requirement by 50%. The 50% recirculation level was selected because it represented the near maximum quantity that could be utilized with a fixed ventilation rate without encountering cabin pressurization problems associated with normal leakage rates and low cabin inflow. Also, advantages associated with more thermodynamically efficient cabin air cooling cycles (e.g., vapor cycles) were considered. The relative changes in block fuel and TOGW are shown in figures 65 and 66 for several different combinations of air-conditioning systems. The effects of adding filters for revitalizing cabin air and associated changes in system equipment weights are included in the comparison. The information shown assumes that ram air penalties will balance. That is, the ram air required by reduced fresh-air systems would be similar to an all-fresh-air system because of the need to condition recirculated cabin air. Also, the potential reduction in cooling air required for the separate compressor systems over bleed air systems would be equivalent to the increased penalty associated with using boosted ram air. The ram air trades are complex and highly configuration critical; thus, an evaluation of associated fuel costs must be made during airplane configuration development. The drag increment due to the momentum exchange resulting from capture of ram air (full momentum loss) for the boosted cabin air system without an associated cooling unit ram air benefit is also shown in figures 65 and 66.

It should be noted that the shaft-driven compressor would allow further fuel savings. However, the effects of shaft-power extraction on engine fuel usage economics will vary with specific engines, and the effect on engine and airplane operational costs will be influenced by such factors as engine location and average airplane flight lengths. Therefore, the advantages to be gained with shaft-driven compressors are configuration critical and must be evaluated for each specific airplane configuration.

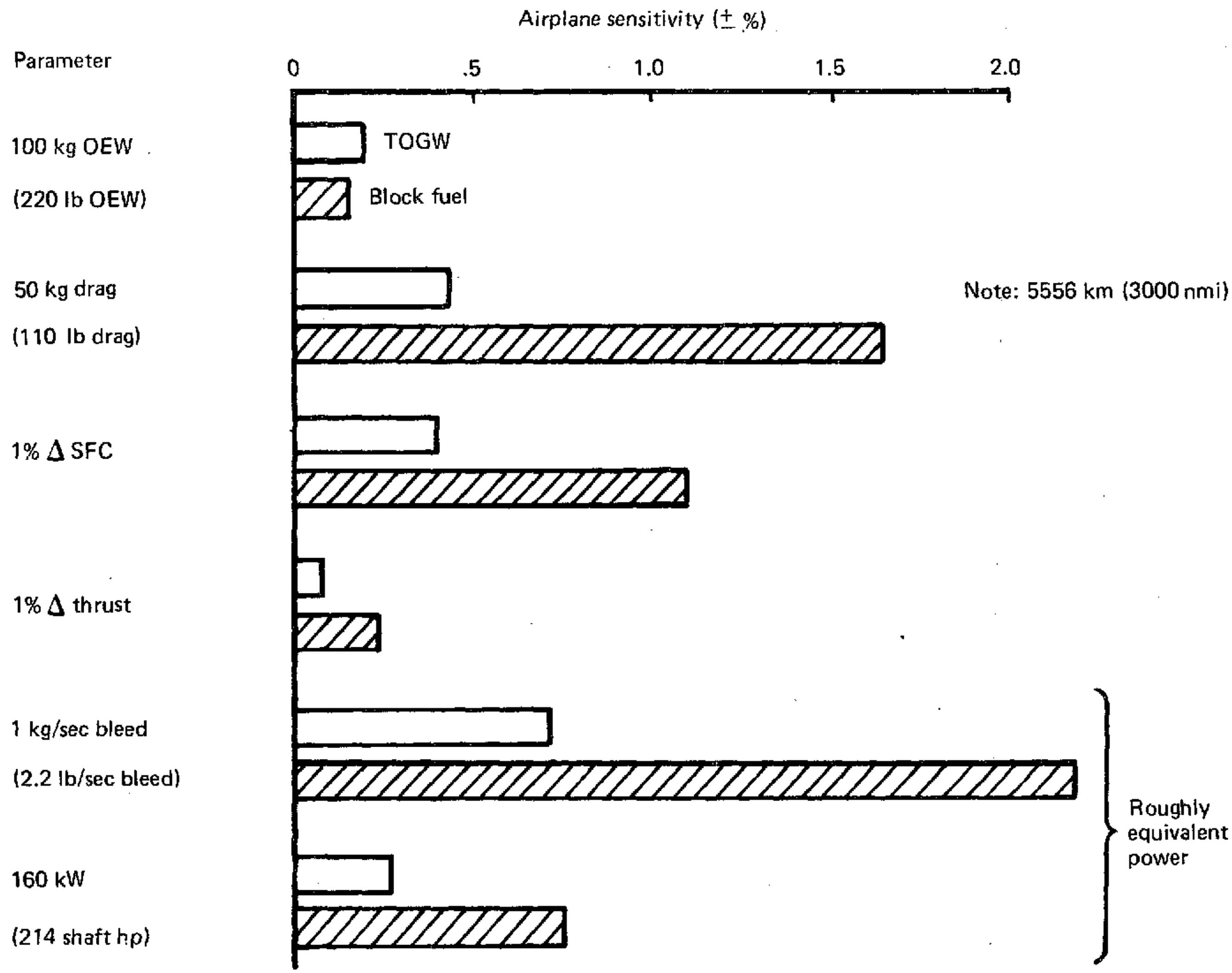


Figure 63.—Sensitivity Factors for Recycling, Secondary Power System Studies

Table 9.—Secondary Power System Sensitivity Factors, Uncycled

Item	Quantity	Factor		
		ΔSFC (%)	ΔFN (%)	Fuel/hr kg (lb)
Engine bleed	1 kg/sec/eng (2.20 lb/sec/eng)	5.46	-10.7	
Engine shaft power	160 kW/eng (214 hp/eng)	2.48	-3.42	
APU power	160 kW (214 hp)			48.5 (107)
OEW	100 kg (220 lb)			3.7 (8.14)
Ram air	1 kg/sec (2.2 lb/sec)			16 to 42 * (35.2 to 92.4)

* Dependent upon ram air system design.

Cruise conditions

Cruise Mach = 0.8
Standard day
9144 m (30 000 ft)

4.6 AIRLINE COORDINATION

It was apparent that several of the aircraft geometric characteristics, systems design approaches, and operational features that offered fuel conservation potential could also impact, in varying degrees, the facilities, personnel, and procedures used by the operating airlines. It was deemed advisable, therefore, to include one or more of the major airlines as participants during the study. The services of American Airlines and United Air Lines were obtained for this purpose by means of subcontracts to those two organizations. They provided valuable assistance to the contractor in the realities of day-to-day airline operational problems as they might be affected by changes to the parameters under study.

The airlines were provided with specific statements of work that called for the following categories of effort:

1. Advisory Inputs
   Each airline was requested to review their operations and establish areas of potential fuel saving that they would recommend be included in this study. They also provided results of some of their in-house studies related to fuel conservation to assist the contractor in making decisions as to analyze specific parameters. (Advice on potential fuel price is one example.)

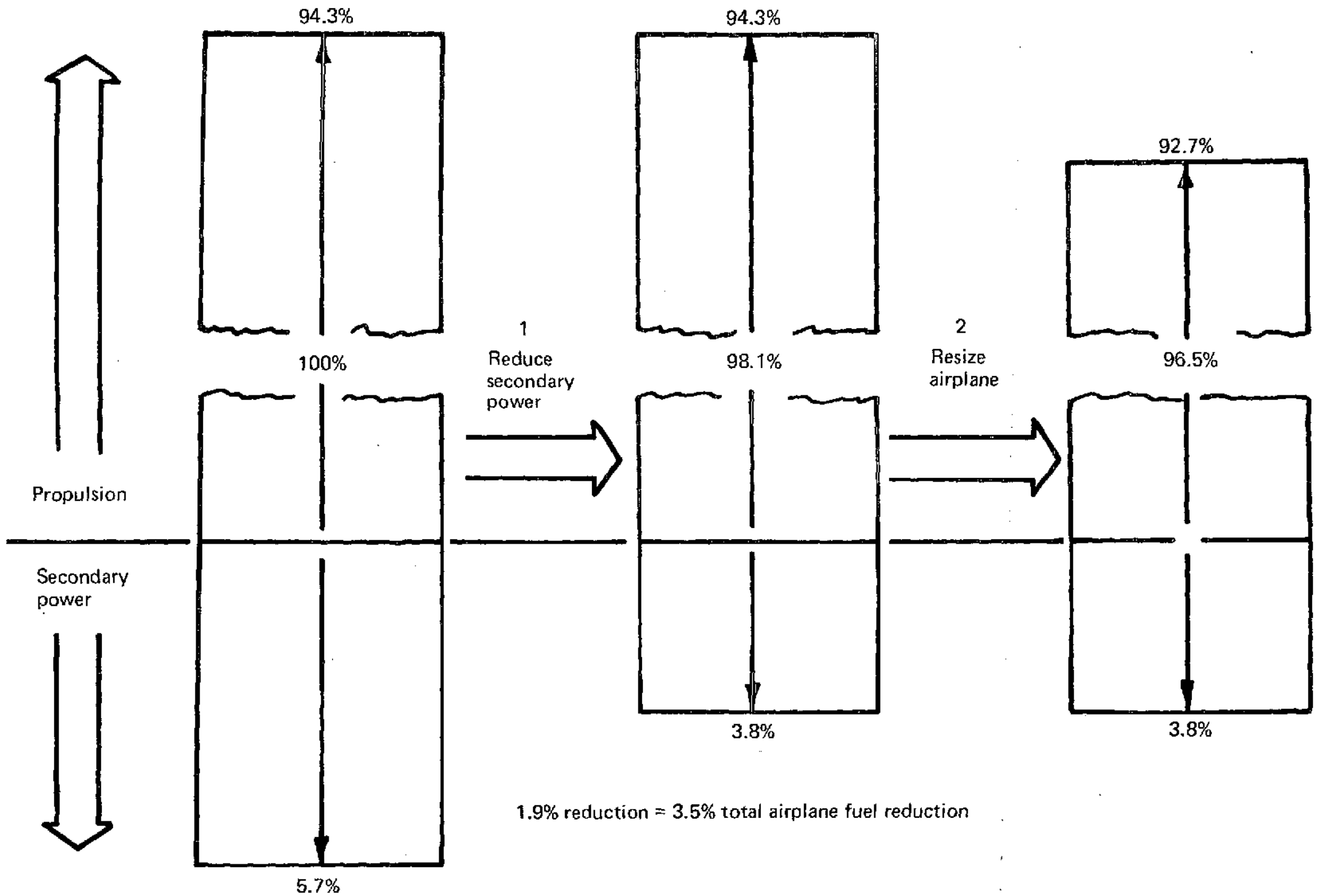


Figure 64.—Effect of Secondary Power System Fuel Usage Reduction on Airplane Fuel Consumption

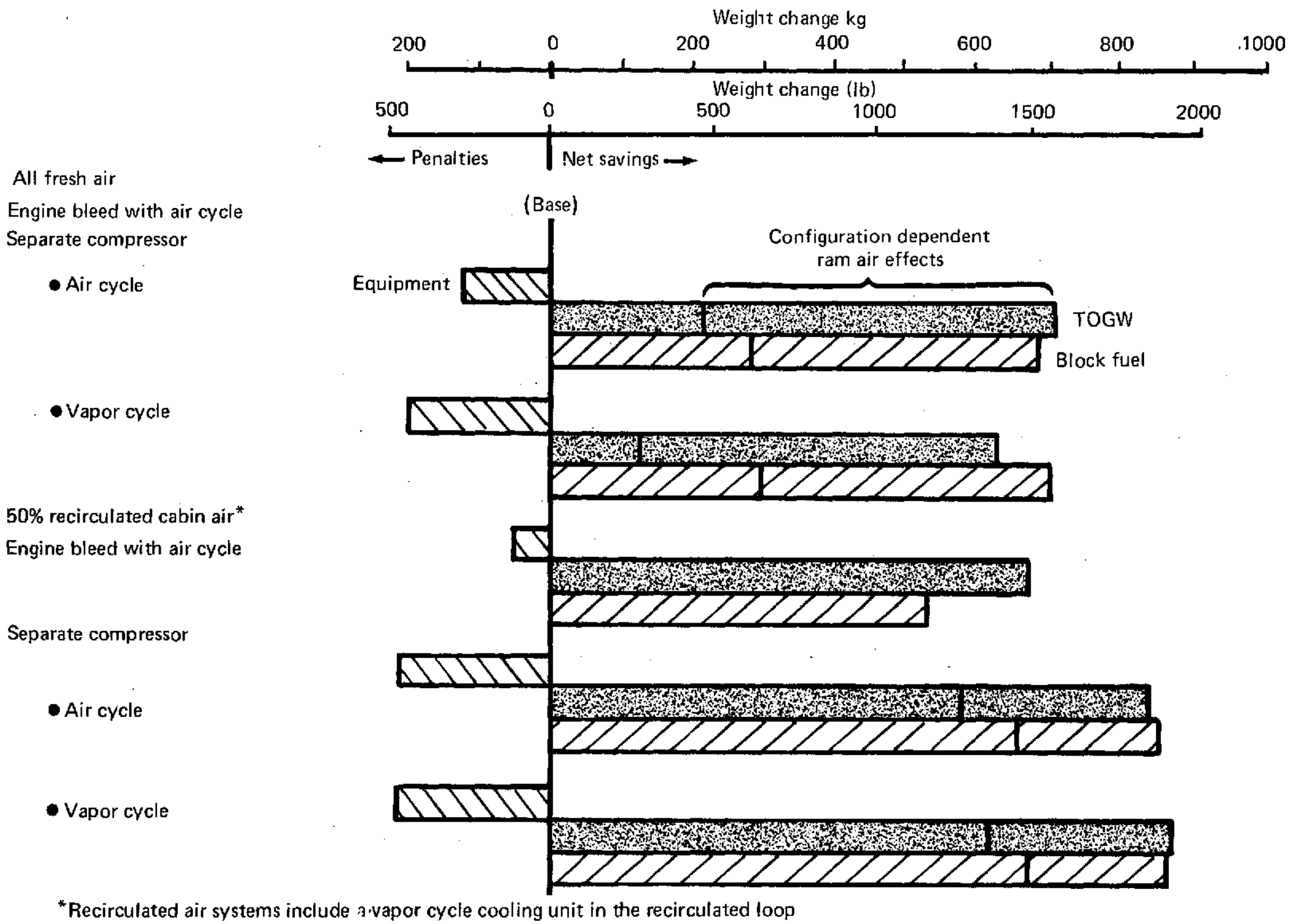
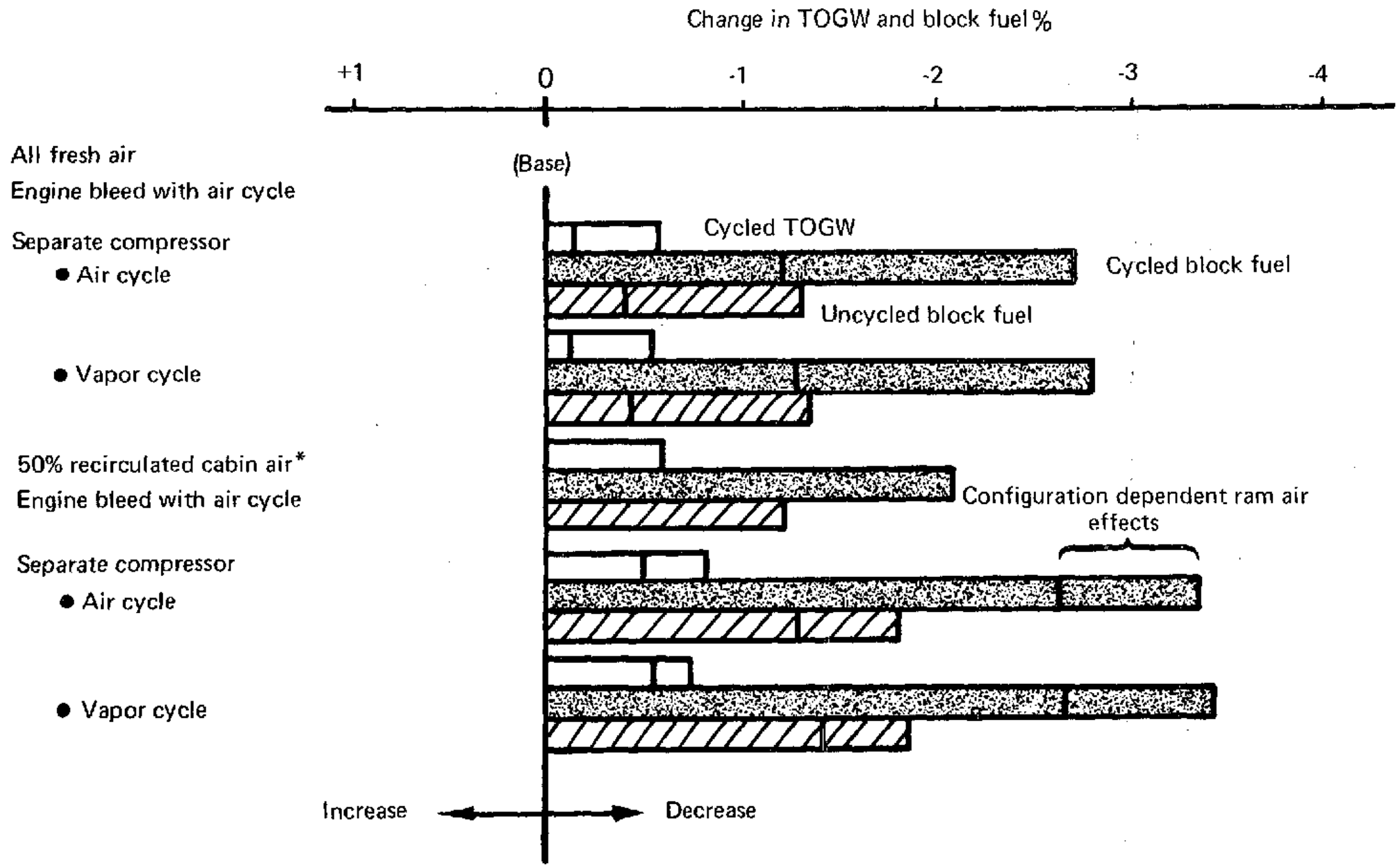


Figure 65.—Air Conditioning System Weight Comparison for Secondary Power System Studies



*Recirculated air system uses a small vapor cycle cooling unit in the recirculated loop

Figure 66.—Air Conditioning System Performance Comparison

2. Specific Analytical Tasks
   Both airlines conducted analytical studies on specific subjects using background data from their historical files as projected for future conditions. Some examples were the effect of cruise speed, aircraft size, and passenger amenities.

3. Critique of Study Results
   Prior to major decisions, key study results were reviewed by the airlines. Results of those reviews were considered and in some cases modified the decisions.

This section summarizes some of the advisory inputs and results of the key analytical studies conducted by the airlines. Where a broad area of interest is involved, this section also includes the integration of inputs from sources other than the airlines, as well as expansion by the contractor. This is particularly the case in the paragraph dealing with the potential cost of fuel and the trends related thereto. Additionally, many of the airline inputs were included in the methods of evaluation and are, therefore, inherent within the results covered by other portions of this report.

4.6.1 DESIGN SPEED

Figure 67 quotes key comments made by the airlines relative to reducing design speed for a 5556-km (3000-nmi) airplane. There was complete agreement opposing reduced design speed except in a truly short fuel-supply situation. The airlines felt that a short-range aircraft with reduced design speed might be acceptable, but even here the comment was qualified by pointing out that tag-end and route-building segments flown by long-range aircraft provide service to many of the short routes.

- "If fuel is limited, optimum fuel consumption overrides regardless of economics. If fuel is available but high priced, fuel consumption is just one variable in economic trades."

BUT

- "It does not appear feasible to introduce new aircraft with markedly lower cruise speed.
- A unilateral move to a speed as low as M = 0.6 would be highly undesirable even if fuel economies resulted.
- As aircraft speed is lowered, the costs directly related to hours flown will increase on a per mile basis."

HOWEVER

- "Modest cruise speed reductions on shorter routes would be acceptable. However, the same transcontinental aircraft fly many of the shorter routes."

Figure 67.—Airline Cruise Speed Comments

United Air Lines made a study of the economic effect of lower cruise velocity on their operation using that portion of their route system served by their DC-10 fleet as a framework. Table 10 summarizes the results. A fuel cost savings of 25% as a result of the lower cruise velocity was assumed. The fuel used in this calculation was priced at 5.8¢/liter

Table 10.—M_{CRUISE} Reduction Effects—UAL DC-10 Fleet Study

	M 0.6	M 0.7
Additional aircraft required (current fleet — 25 aircraft)	8	3
Additional operating costs (assumes 25% fuel reduction)	$65 000/day*	$18 000/day*
Inadequate departure times (%)	57	32
Connecting bank missed (%)	100	75

*Does not include cost of processing additional aircraft, additional meals served, or additional flight crews in overall fleet.

(22¢/gal). The results show a significant economic penalty resulting from the lower cruise velocity in spite of the assumed large fuel saving. The results of this study also indicate a dislocation of the system, which would seriously affect the service offered the traveling public, as well as imposing additional uncalculated economic and competitive penalties on the operator.

Estimates of fleet fuel usage to service a basic system requires that fuel burn per hour be calculated to bring airplane productivity into the analysis. If it is assumed that a 25% saving in fuel burn per hour can be achieved by slowing a CWB-E type airplane from M = 0.8 to M = 0.7, the fleet usage will decline by 16% for the fleet operating the route system United Air Lines studied (July 1973, DC-10 usage by UAL). Total route miles on this system total 181 370 km (112 722 nmi). Total fuel burn calculations for CWB-E were made for each segment of this system and compared with the same value reduced by 25% per hour for these flights at M = 0.7 with delays equal to the estimated factor in the United Air Lines schedule. The fuel burn per passenger mile also declines by 16% for the fleet using these assumptions. If, however, the saving in fuel burn per hour is assumed to be only 10%, resulting from the cruise velocity reduction to M = 0.7 from M = 0.8, the system fuel burn will increase slightly (< 1%). The fuel per seat kilometer will also show a negligible increase. Therefore, a 10% per hour saving in fuel consumption is approximately balanced by a 12% decrease in cruise velocity in terms of fleet fuel usage. Table 11 shows the above data and compares it with the TAC/Energy airplane fuel burn, which was estimated on the same United DC-10 system.

If the airline endeavored to fly fewer frequencies at higher load factors instead of adding airplanes to the fleet in order to carry the same number of passengers, the load factor on a 196-passenger airplane would only need to increase from 55% to 60% to theoretically accommodate the expected traffic. However, the practicality of such an operation may be questioned. The average daily frequency on routes serviced by transcontinental-range aircraft is approximately four frequencies a day, and many are served only once per day. High density routes such as Chicago to Dallas/Fort Worth (29 frequencies by two airlines) could be serviced by fewer frequencies at higher load factors, disregarding airline

Table 11.—Fleet Fuel Usage Estimate

	Fuel burn per A/C per day, kg (lb)	Block time per 1000 nmi trip, hr	Fleet size	Fleet fuel burn per day, kg (lb)	Delta fuel, kg (lb)
CWB-E V_{CR} = M 0.80	45 903 (101 200)	2.95 (from 1973 UAL schedule)	25	1 147 583 (2 530 000)	Baseline
CWB-E V_{CR} = M 0.70	(Assume 25% reduction in fuel burn per hour) 34 427 (75 900)	3.35 (calculated from 1973 UAL schedule)	28	963 969 (2 125 200)	183 613 (-404 800) -16%
TAC/Energy V_{CR} = M 0.80	31 456 (69 350)	2.55 (assumes std delay, only)	25	786 412 (1 733 750)	361 171 (-796 250) -31%

1974 route system requiring
25 A/C, V_{CR} = M 0.82

Average trip = 1852 km (1000 nmi)
Utilization averages 10 hr/day

competitive pressures. However, routes such as Denver to New Orleans or Houston to Philadelphia cannot be served on a reduced frequency basis without drastic impact on service.

4.6.2 UTILIZATION

A key factor in determining operating costs on an airplane kilometer or on a seat kilometer basis is the number of trips per year. Any mathematical calculation of trips per year will show variation in the result as block time varies. The airlines have consistently pointed out that a small change in block time will not generate different numbers of trips per year as a matter of practical, scheduled aircraft utilization. The number of trips per year affects that amount of cyclic maintenance charges, allocation of annual costs for insurance, and allocation of the book charge for depreciation of the equipment.

American Airlines studied the problem and derived a formula for calculating trips per year as a function of block time, estimated gate time, and maintenance time. The American Airlines formula and the applicable portion of the ATA formula are shown in figure 68. Figure 69 compares calculations made by the American Airlines formula with those made by the standard ATA formula. It takes several key items into account that are not addressed by the ATA formula, such as gate time, maintenance downtime, etc. With slight modification, the American Airlines approach was used in lieu of the ATA formula for the evaluation portion of this study. The assumption was made that changes in cruise Mach

ATA formula

$$\bullet\ U = \frac{\dfrac{4275}{\left(1+\dfrac{1}{T_b+0.3}\right)}+475}{365}$$

Where
U = daily utilization (hr)
T_b = block time (hr)

$$\bullet\ n = \frac{U}{T_b}$$

Where
n = average trips/day

AAL method formula

$$\bullet\ N = \frac{24}{(X+Z)+[(Y+1)\ (T[L,M])]}$$

Where

	Parameter value for this study
N = maximum trips/day	
X = maintenance down time/departure	–0.8 hr/departure
Y = maintenance down time/ramp hr	–0.45 hr/ramp hr
Z = gate time requirement	–0.58 hr/departure
T = block time (function)	
L = stage length	
M = cruise Mach number	

$\bullet$ n = NU
Where
n = actual trips/day
U = usage factor (function of block time) –0.7

Therefore
$n = f'\ (N,U;T)$

Figure 68.—Trips/Day Calculation Formula Approaches

number less than 0.03 would be disregarded. The same number of trips as aircraft with the higher cruise velocity was assumed in such case.

4.6.3 PASSENGER AMENITIES

Both subcontractors provided data indicating that present levels of passenger comfort and service should not be compromised.

4.6.4 ADDITIONAL AIRLINE PARTICIPATION

Many questions relating to procedures, expert opinion, method, etc. were referred to the airlines. They played an active part in assisting in developing the method for economic evaluation and in providing economic guideline values of accounts from airline records (see sec. 6.2.3).

The participation of American Airlines in the Payload study is discussed in section 4.7.

4.6.5 COST/FUEL SAVINGS TRENDS AND TRADES

This section discusses some of the trends and trades derived by the contractor from airline data.

Each of the recommended features from the sensitivity studies makes small improvements in overall fuel consumption and the airline operating economics. This is true because the features recommended are neither expensive nor complex, and airplane price and maintainability change very little as a result of each feature.

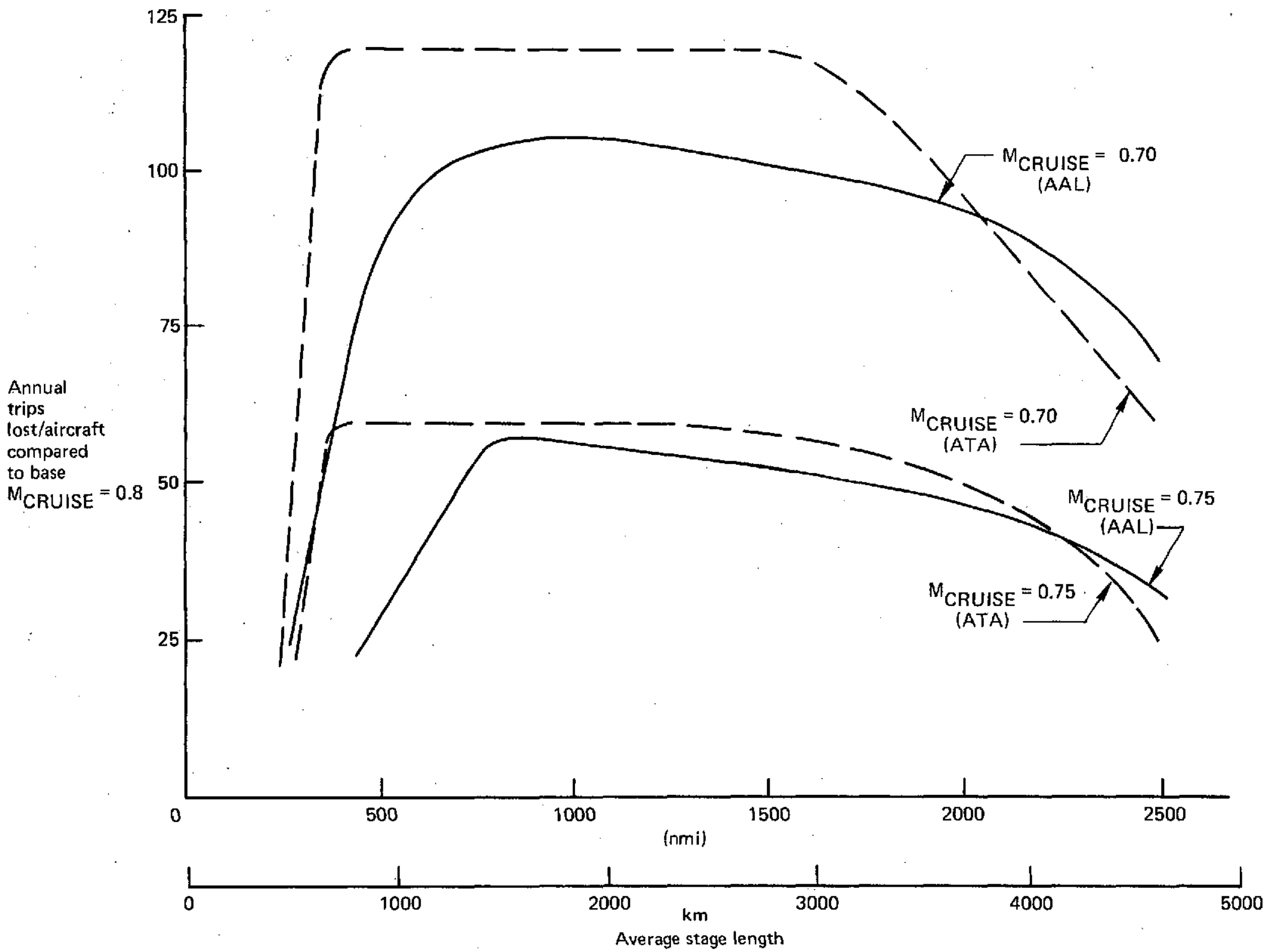


Figure 69.—M_{CRUISE} Effects on Trips Lost Formula Comparison

Two areas show promise of providing significant fuel reduction and also of providing economics of sufficient magnitude to attract considerable attention in the future as a result of the TAC study (ref. 2) and the sensitivity studies.

1. Reduction of Congestion
   Technology changes designed to maximize runway acceptance rates, aircraft with payloads that closely approximate demand without increasing frequency, airport improvements, and more disciplined competition among airlines all have great potential for reducing delay. More fuel and operating expense can be saved in this area than in any improvement in operations defined to date.

2. High Capacity Aircraft
   There is a potential for fuel saving in large aircraft by using unconventional cabin arrangements such as double-deck configurations. This is discussed in greater detail in section 4.7.2. Fuel savings on a seat kilometer basis, as well as operating economies, were significant for this type of aircraft. However, the concept is only suitable on very large aircraft, and in order to be fuel conserving or economic, these aircraft can only operate on high traffic-density routes.

The economics of the concept of saving fuel by designing for lower cruise velocity may be summarized by a very large interrogation point. The whole question of the advisability of a significantly lower cruise velocity for a transcontinental airplane was considered to be a function of three factors which are discussed in the following paragraphs.

1. Fuel Availability
   Will adequate fuel be available at prices which are different from today's prices?

2. Fuel Price
   What will be the price of fuel in real dollars?

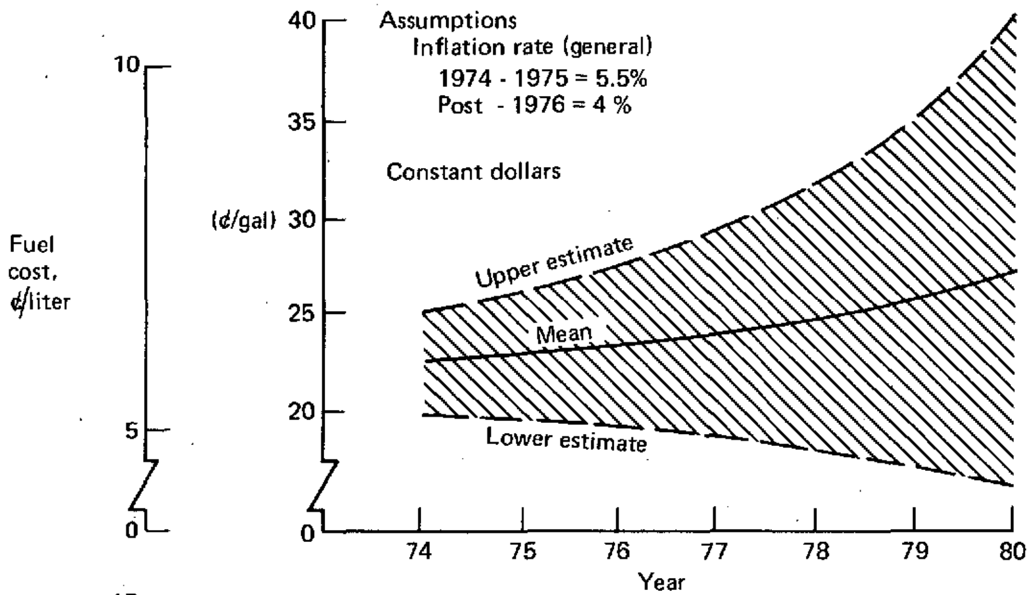
3. Duration of Availability or Price-Crisis Conditions
   If the answers to questions 1 and 2 indicate the advisability of a lower cruise velocity design, will the conditions continue for a long enough period of time to make an airplane program based on such a design economically viable?

4.6.5.1 Fuel Availability

The consensus was that there will be adequate fuel available but at prices which may in themselves be an incentive to fuel conservation. This was not a unanimous opinion; all sources recognized the uncertain world political and economic factors that influence the availability of fuel. If this consensus is proven wrong, drastic measures for fuel conservation would become a necessity regardless of economics.

4.6.5.2 Fuel Price

Figure 70 shows the spread of estimates received from airline, airframe, Government, and financial experts who have studied the fuel problem. Predictions are shown in "then year dollars" and in constant dollars. The lowest prediction is based on the theory that fuel



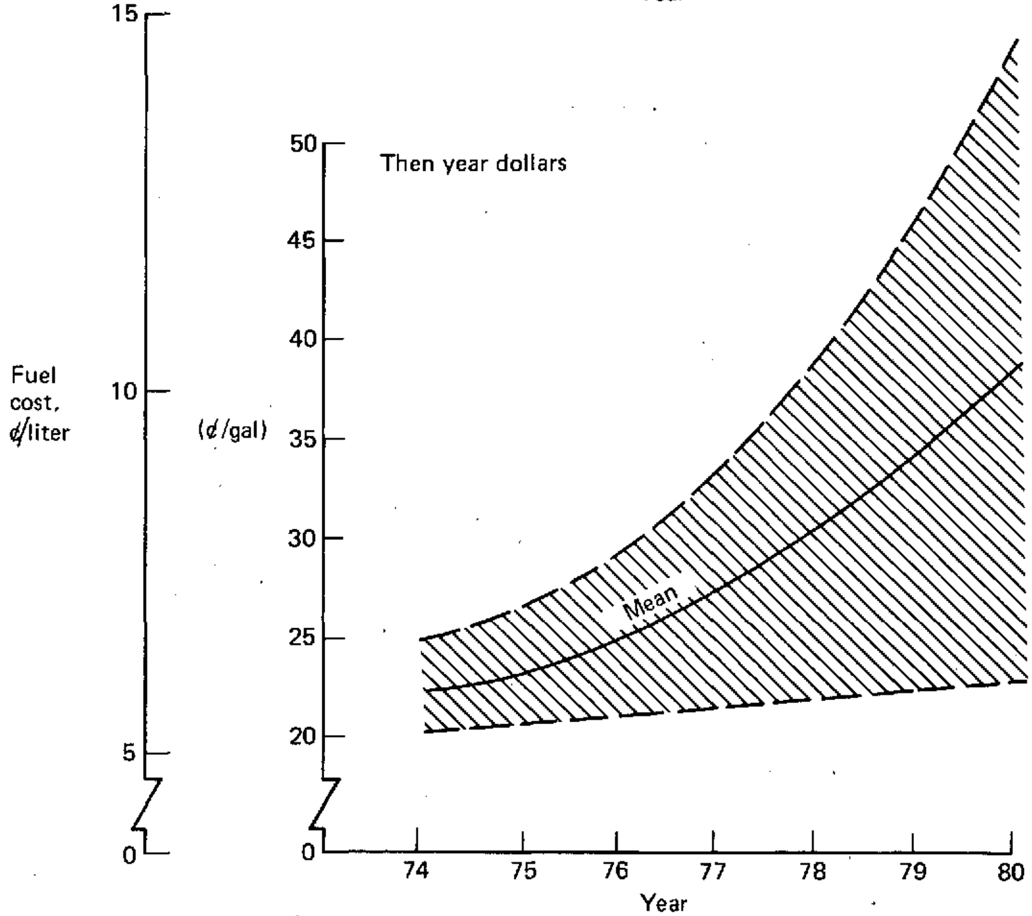


Figure 70.—Estimated Fuel Price

prices have escalated during the past year and will essentially level off with only small increases in the future (see then year dollars prediction, fig. 70). Inflation is assumed to continue into the 1980's, and the escalation of other factors (maintenance, labor and materials, crew pay, etc.) will be at higher rates than the escalation of fuel prices. Therefore, fuel prices in constant dollars will decline.

Review of other data sources with equal credibility indicate the fuel price escalation will continue at the same rates that have been experienced in the immediate past. No one really knows nor does any expert have a high probability of predicting fuel price in the future.

Figure 71 shows the difference the assumed level of fuel price makes in making economic trades and evaluation of future aircraft. A 1973-74 breakdown of direct operating costs of a particular aircraft are shown from historical data. A 1980 breakdown is shown twice; first using the lower estimate of fuel at 6.3¢/liter (23.8¢/gal) and amounting to 30.6% of the total DOC. The second shows the breakdown using the mean of the estimates, 10.3¢/liter (39.1¢/gal), for fuel which equates to 39.9% of the DOC. Fuel conservation measures will yield the largest payoff for the high-cost fuel condition.

Figure 72 indicates how this difference can affect trades. The chart shows comparison in terms of DOC between any percentage increase or decrease in fuel consumption and a resulting change in block time. Trades made on the fuel price 4.8¢/liter (18¢/gal) line will yield different results than those made on the fuel price 7.9¢/liter (30¢/gal) line.

This study presents results using 5.8¢/liter (22¢/gal) 1974 dollars, and 7.9¢/liter (30¢/gal) 1974 dollars, which would reflect a 36% increase in price in constant dollars. True value probably falls between these extremes.

4.6.5.3 Duration of Fuel Availability or Price-Crisis Conditions

Statements have been made that legislation could put a speed limit on aircraft in the same manner that has been applied to automobiles. It is assumed that such an action would in itself create a market for an aircraft designed to fly at lower speeds, since the latter would be more economical than merely flying a higher-speed aircraft at slower speeds. However, there would have to be assurance that these conditions would be continued for a long period of time before an airline could afford to invest huge sums in a new airplane program. Even longer term commitments would be necessary to induce an airframe manufacturer to risk developmental funds for such a program. Subsequent legislation could alter any such rule at any time; the risk of such action would be too great to warrant the commitment to development of aircraft tailored to fit a specific rule.

4.7 PAYLOAD STUDY

The objective of the study was to determine the trend effect of transport size (number of passengers) on total fuel consumption and operating economics when service frequency, load factor, and passenger acceptance (effect of turnaways) are allowed to vary while the aircraft are operated on a representative portion of the domestic route system under projected passenger traffic conditions. The impact of delays and other congestion

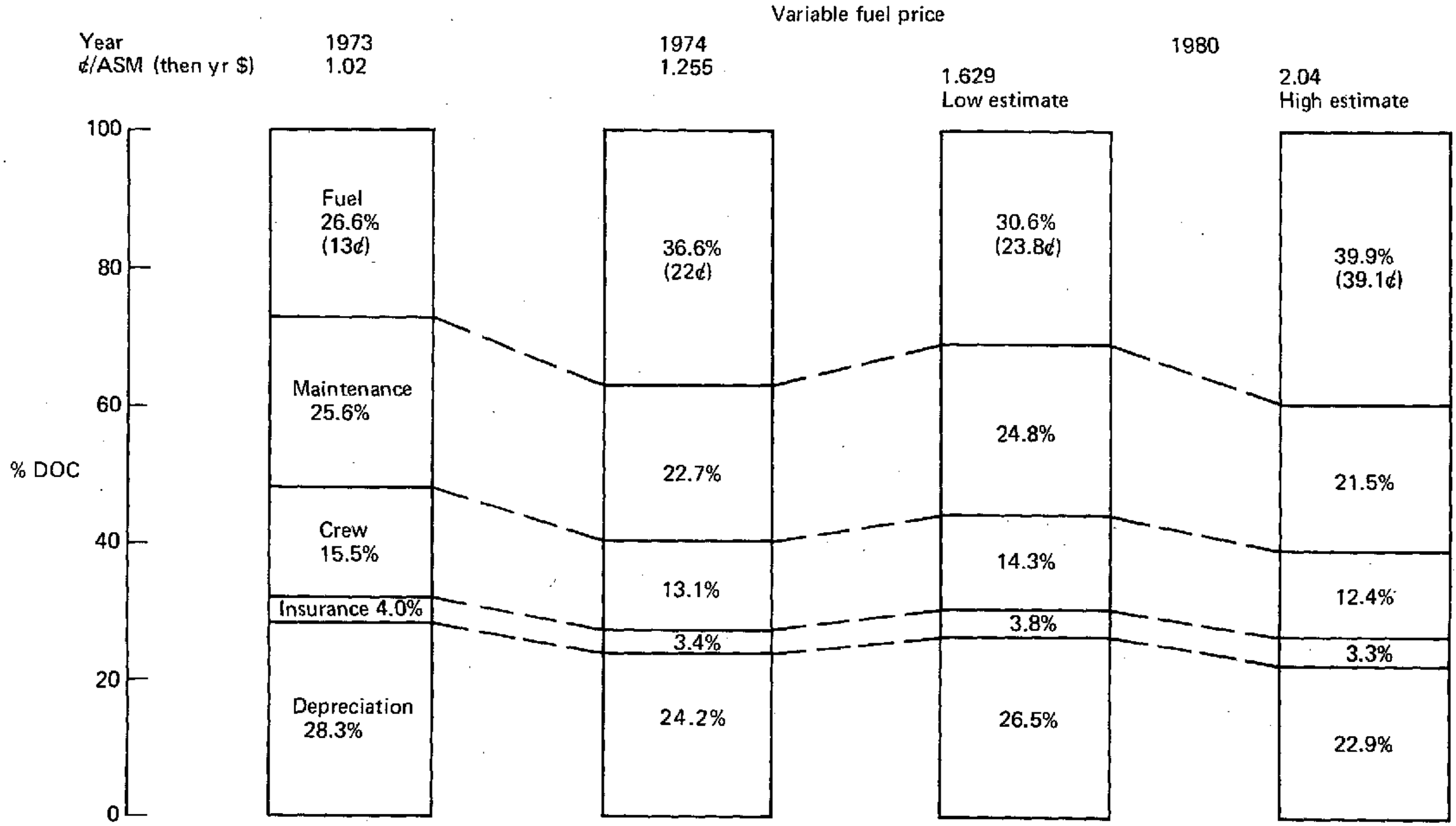


Figure 71.—Trend of DOC Elements

SENSITIVITY OF DOC TO CHANGE

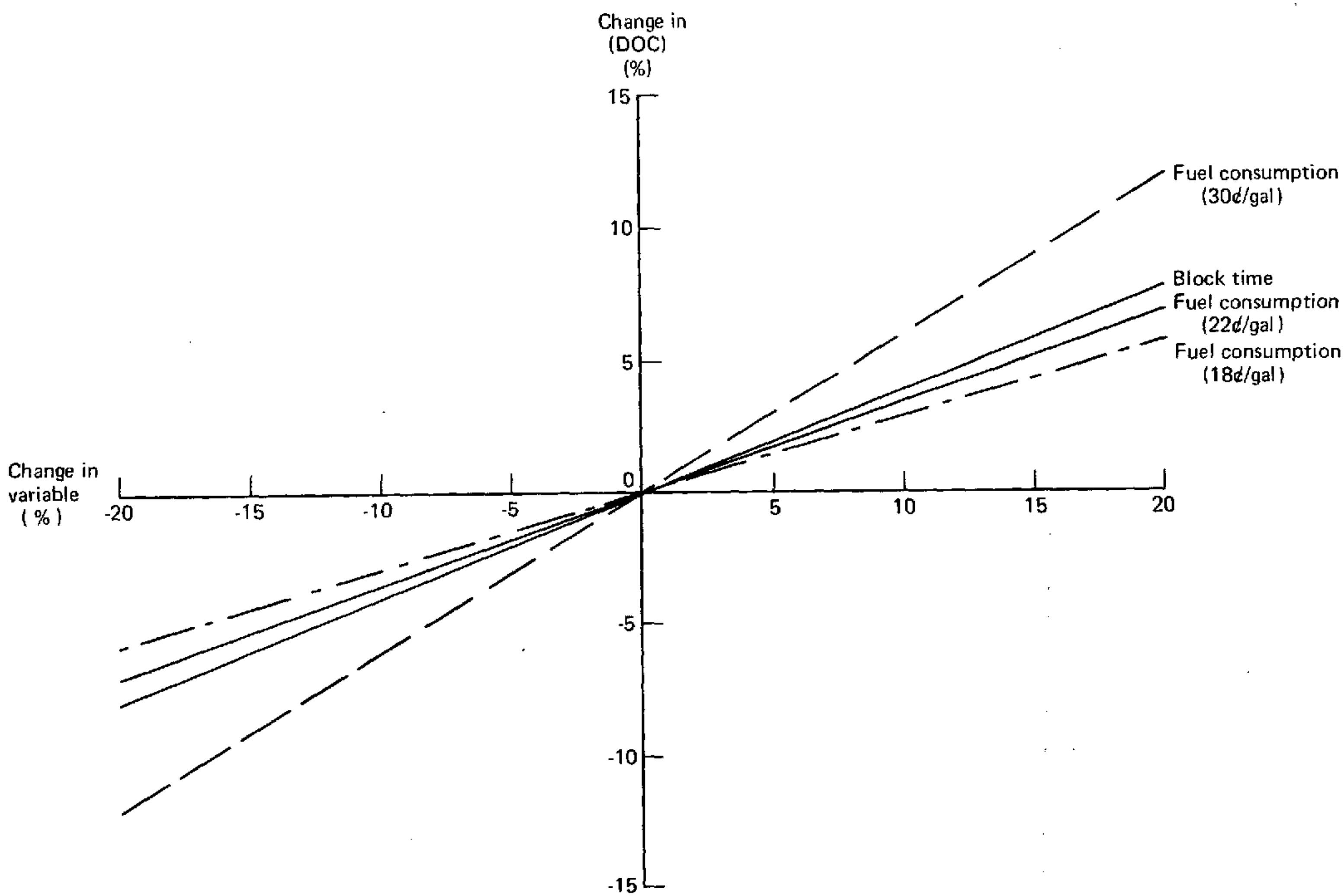


Figure 72.—Sensitivity of DOC to Change in Variables

parameters affected by aircraft size, frequency, and load factor on fuel consumption and economics were an inherent part of the study.

Figure 73 shows the approach that was followed. American Airlines provided a representative portion of its route system, the August 1973 traffic on those routes, and an estimate of the minimum frequencies required to provide adequate passenger service in a competitive environment. Two traffic growth factors identified as case I and II were used.

Inspection of these data yielded an estimate of the size of initial aircraft candidates for fleets of transcontinental range in the U.S. domestic route system. These aircraft were configured, and the estimated performance for each was calculated.

These data were used for iterative runs on a computer model designed to determine optimum size fleets under specified conditions. In this evaluation, the number of frequencies was held to the minimum necessary for adequately servicing the route. Load factors were allowed to climb to a 65% to 70% range. A second analysis was made with load factors held to 60%. With these restrictions, the program calculated the average fleet size and load factor, expected profit levels and fuel burn for the fleet, as well as the expected percentage of turnaway passengers during peak periods. The turnaway calculation was taken as a figure of merit relative to providing adequate service to the general public. Estimates of these same parameters were made under conditions where a 20% increase in frequency with an estimated increase in delay resulting from such a frequency increase.

4.7.1 PAYLOAD SIZES INVESTIGATED

Preliminary size estimates were made by inspection of the traffic data for the representative system when grown by a factor of 2.2 for case I and by 3.2 for case II. Rough estimate was made of the size aircraft required to service this traffic when frequency was held to the minimum levels suggested by American Airlines. This inspection method indicated a possible requirement for aircraft with approximately 196 seats, 350 seats, and 500 seats. Aircraft with these capacities were configured and evaluated.

4.7.2 PAYLOAD STUDY CONFIGURATIONS

A study of body shape and interior arrangements was conducted prior to making a complete configuration of the 500-passenger and the 350-passenger airplanes to be compared with the 196-passenger baseline airplane.

The selection of seating arrangement was based on the body fineness ratio study summarized in figure 74. The forebody and aftbody were contoured in conjunction with the fineness ratio to minimize body drag. This figure indicates that for double-aisle, single-deck configurations the wetted area and fuselage length are becoming excessive at 450-passenger capacity.

Single-deck and double-deck body arrangements were designed for both the 350- and 500-passenger airplanes. A comparison of design features is shown in figure 75. The single-deck arrangement was selected for the 350-passenger airplane, since there was no significant gain in using the double-deck arrangement for this capacity requirement. The

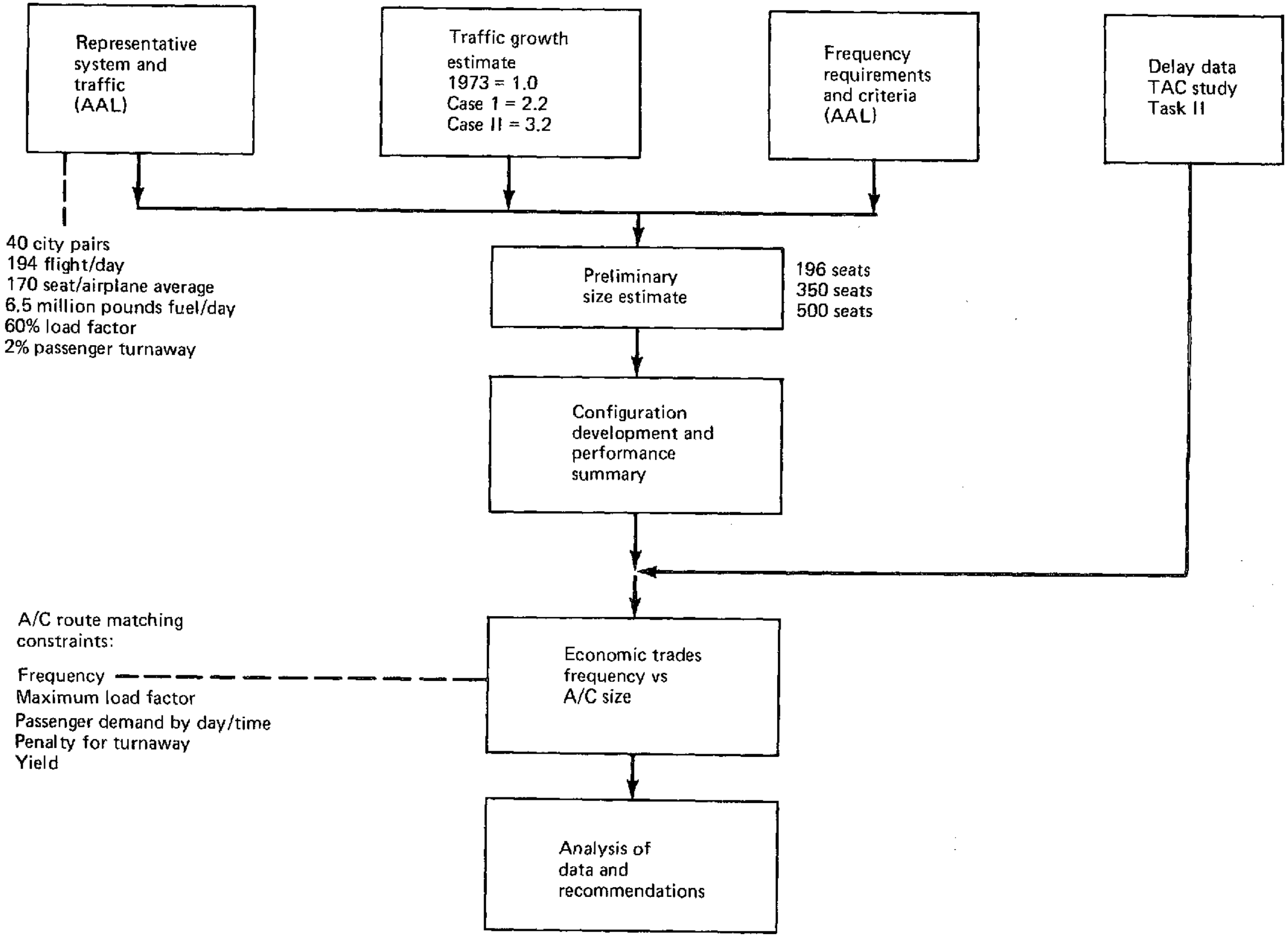


Figure 73.—Payload Study Outline

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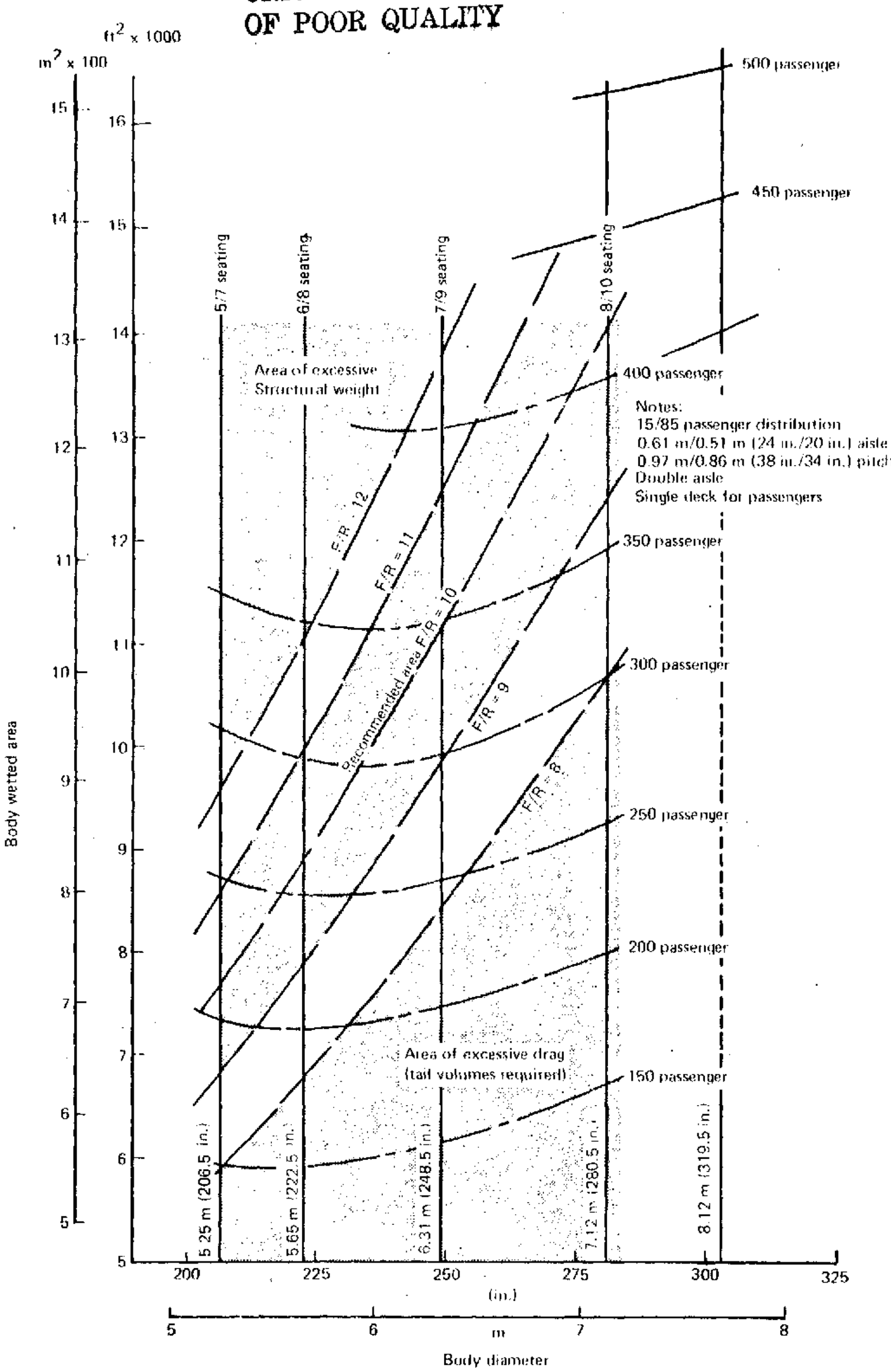
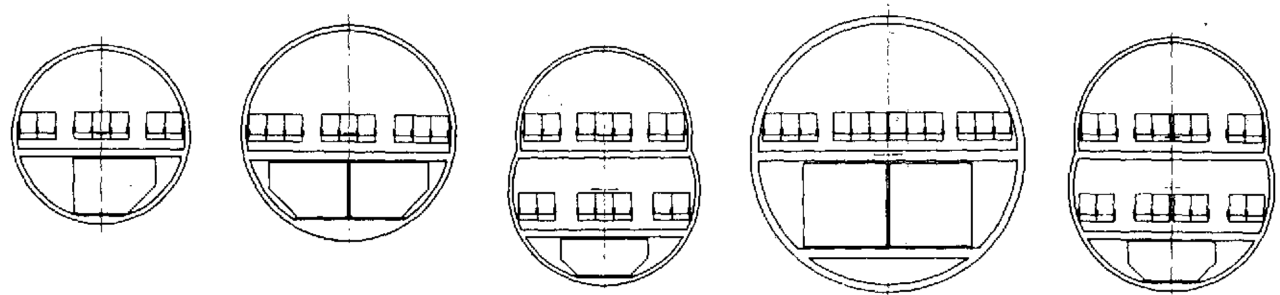


Figure 74.—Passenger Loading Study Summary



	196 passenger Single deck (baseline)	350 passenger Single deck	350 passenger Double deck	500 passenger Single deck	500 passenger Double deck
Seating (first/tourist)	5/7	7/9	5/7	10/12	6/8
Diameter – m (in.)	5.25 (206.5)	6.36 (250.5)	5.20 (204.9) 5.65 (222.6)	8.12 (319.5)	5.83 (229.6) 6.17 (242.0)
Wetted area – m^2 (ft^2)	710 (7600)	1060 (11 400)	790 (8500)	1520 (16 400)	980 (10 500)
X - section area – m^2(ft^2)	21.6 (232)	31.3 (337)	31.9 (344)	51.7 (557)	35.7 (384)
Fineness ratio	9.58	10.27	7.75	9.16	8.46
Sill height -m (in.)	3.65 (144)	5.41 (213)	3.25 (128) 5.59 (220)	6.93 (273)	3.99 (157) 6.35 (250)
Container volume -m^3 (ft^3)	34 (1200)	127 (4500)	34 (1200)	325 (11 500)	57 (2000)

Figure 75.—Body Cross-Section Comparison

double-deck arrangement was selected for the 500-passenger airplane because the wetted area and cross-sectional area were considerably better.

The selected airplane designs were evaluated for weight and balance, stability and tail sizing, engine and wing sizing, and airplane performance. Comparison of the resulting configurations is shown in table 12 and figures 76 and 77.

Table 12.—Airplane Comparisons

	196 passenger (baseline)	350 passenger single deck	500 passenger double deck
Design payload—passengers	196	350	500
—kg (lb)	18 140 (40 000)	32 400 (71 400)	46 250(102 000)
Relative gross weight	1.00	1.70	2.08
Relative wing area	1.00	1.84	2.32
Relative body length	1.00	1.29	1.50
Relative body diameter	1.00	1.21	1.11/1.17
Relative thrust/engine	1.00	1.62	1.94
Relative fuel (100% load factor)	1.00	0.85	0.71
Relative DOC (55% load factor, 1852 km (1000 nmi), 5.8¢/ℓ (22¢/gal) fuel, ATA)	1.00	0.74	0.59

Common characteristics:

Design range	5556 km (3000 nmi)
Cruise Mach	0.80
Engine BPR	6
TOFL	2530 m (8300 ft)
ICAC	9150 m (30 000 ft)
V_{APP}	65 m/s (127 kn)
Aspect ratio	12

The large payload aircraft with high aspect ratio were evaluated for potential gate and ramp problems. Space layouts were made using United Air Lines terminal area at Chicago's O'Hare Airport. See figure 78 for comparison of the 350- and 500-passenger airplanes with 747's. The 500-passenger airplane with AR 12 wing would have restricted passage under some circumstances. Although fewer aircraft could be accommodated at the terminal, the true impact would require taking into account the passenger quantity flow through the terminal, which was beyond the scope of this study.

4.7.3 ROUTE SYSTEM USED

Figure 79 shows in simplified form the route system used in the study. The chart is drawn showing only the city pairs served rather than the myriad of variations of flights through major hubs that were included in the study. For example, the city pair New York to Chicago is represented by a single line. That line represents 23 flights, most of which originate and/or terminate at places other than New York and Chicago. The study network contained 40 city pairs with 194 flights per day.

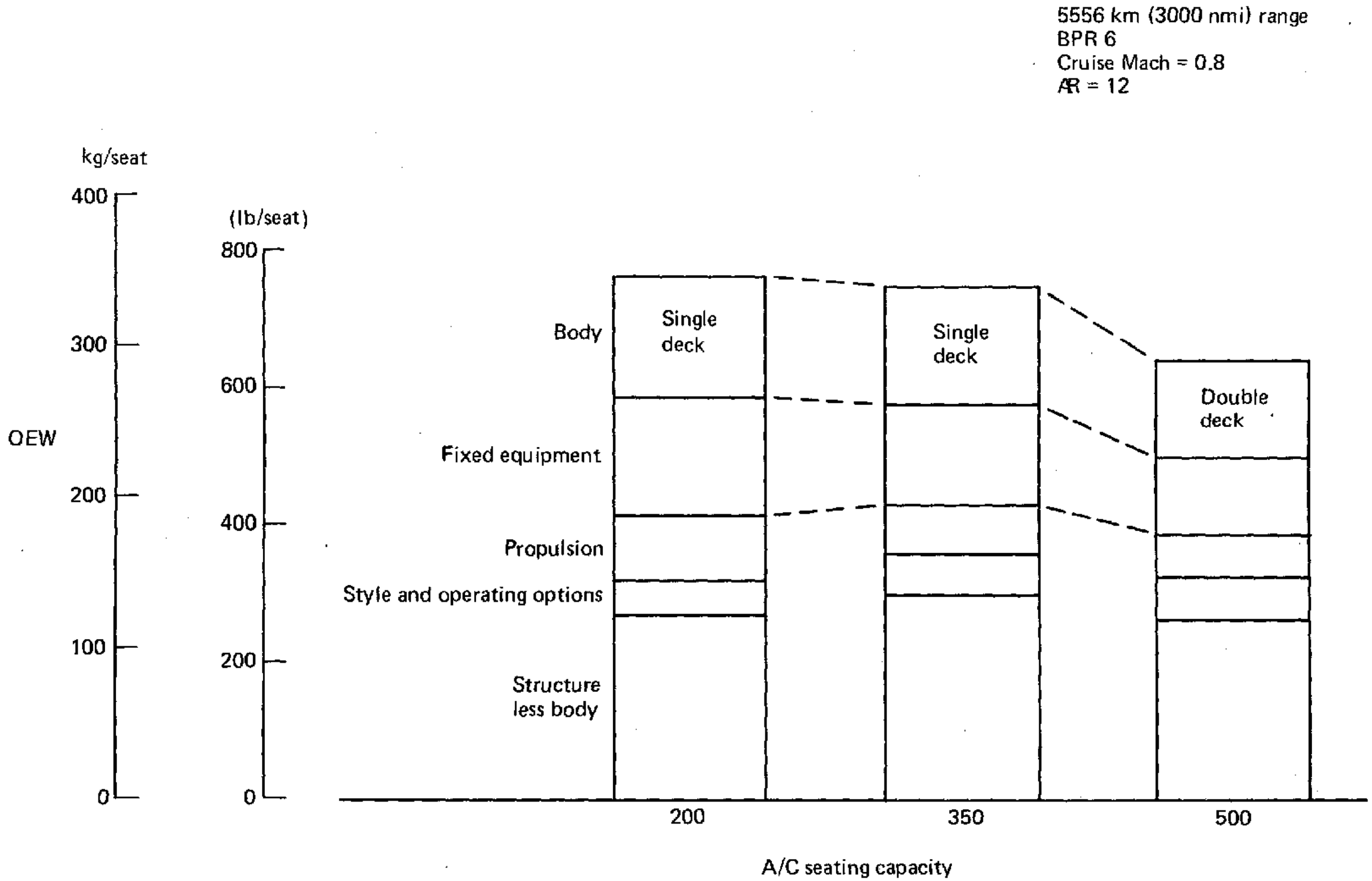


Figure 76.—Weight Breakdown

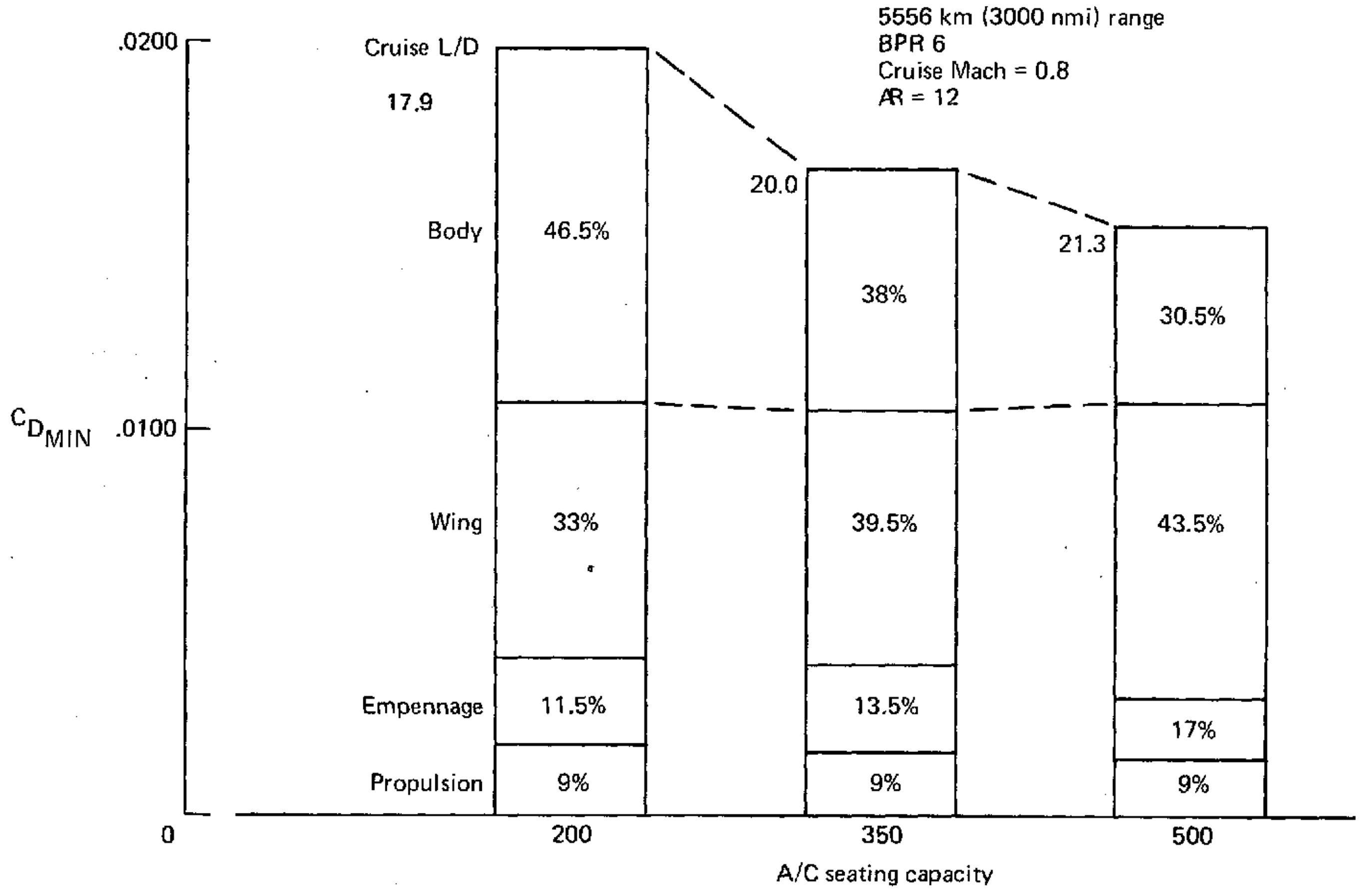


Figure 77.—Drag Breakdown

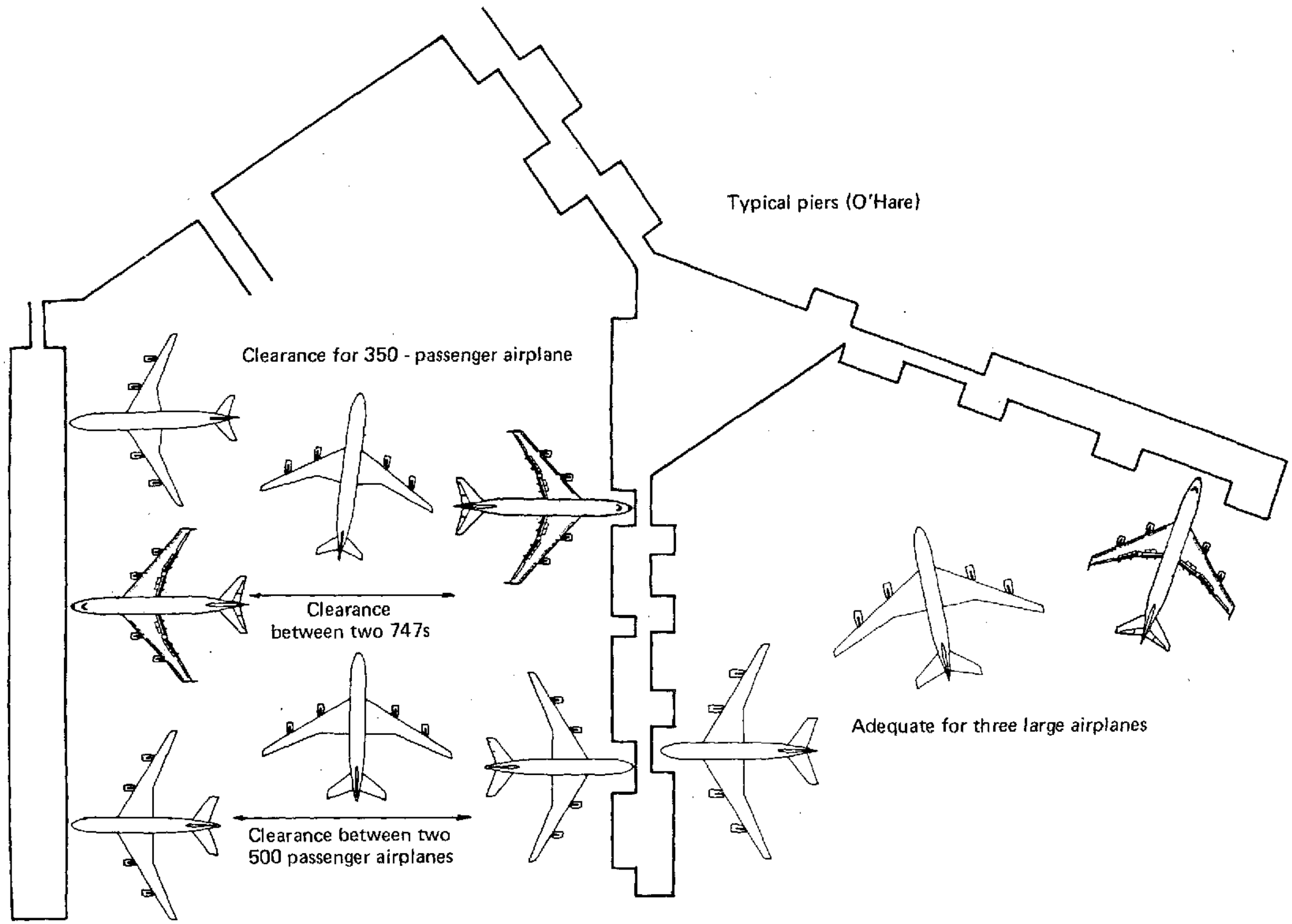


Figure 78.–United Air Lines Terminal Area–O'Hare Airport

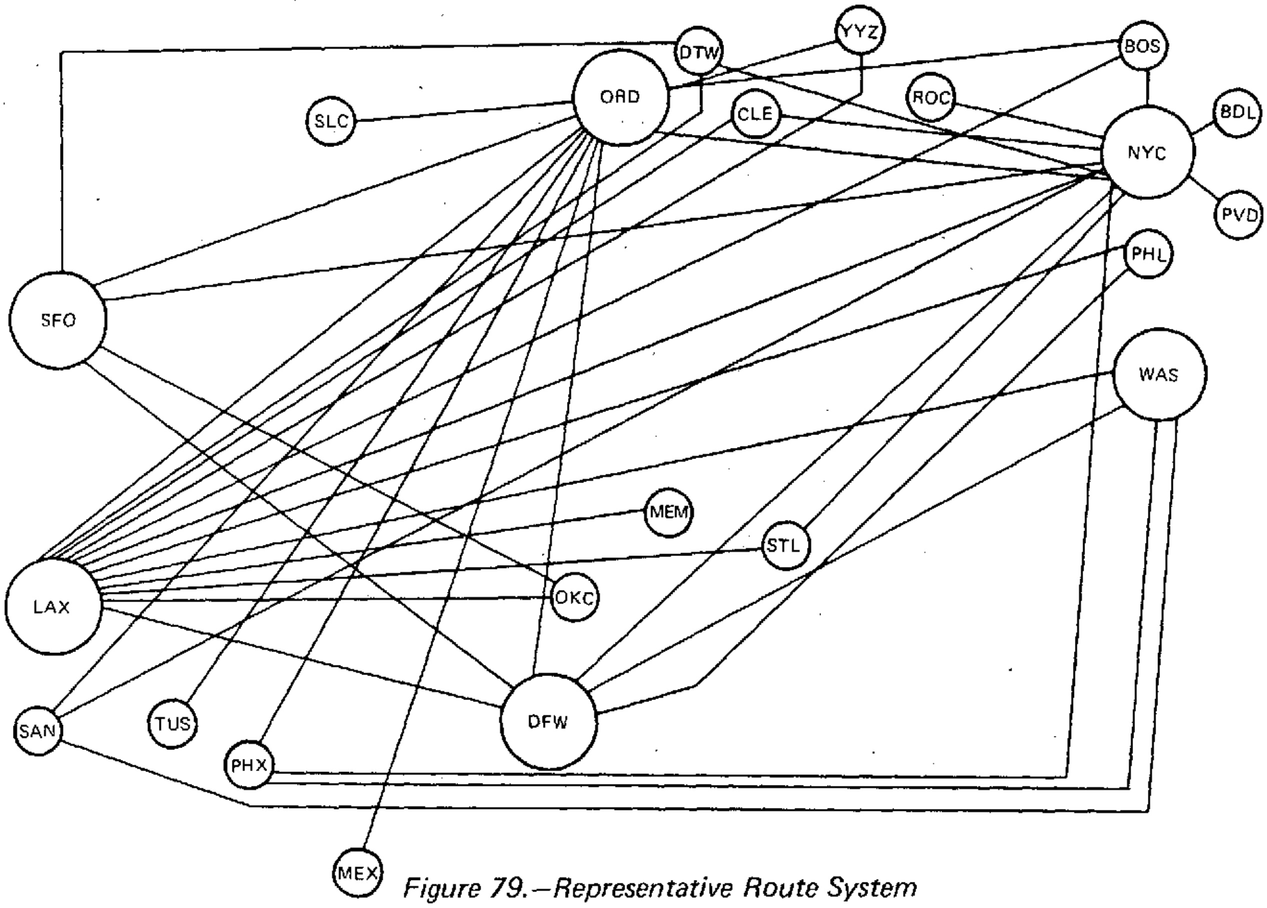


Figure 79.—Representative Route System

The system included, but was not confined to, the three major airports studied in detail in reference 2; Los Angeles International (LAX), O'Hare International Airport (ORD), and John F. Kennedy International Airport (JFK). It also included traffic between less busy airports such as Oklahoma City (OKC), Salt Lake City (SLC), and Rochester (ROC). Transcontinental and semi-transcontinental routes predominated for a 5556-km (3000-nmi) design range airplane. However, short-feeder and tag-end routes such as New York to Hartford, Connecticut were included.

4.7.4 PAYLOAD TRENDS FOR MINIMUM FUEL AND COST

Figure 80 indicates the trends that resulted from the study. The left side of the chart shows relative fuel usage and DOC's per seat kilometer. Fuel usage and operating costs become significantly less as the airplane size increases.

The right side of the chart shows the reverse trend when fuel usage and DOC's on a dollar per airplane-kilometer basis are examined. As expected, the larger airplanes use more fuel and cost more to operate than the smaller airplanes. This would apply whether reasonable load factors were achieved or not.

In conclusion, economies of fuel and operating costs may be realized through the use of large airplanes when it could be assured that there would be sufficient passengers to fill a reasonably large percentage of the available seats. The use of large aircraft on low traffic density routes (as at low demand time of day) would waste fuel and money. Although there

5556 km (3000 nmi) range
BPR 6
Cruise Mach = 0.80
1852 km (1000 nmi) stage length

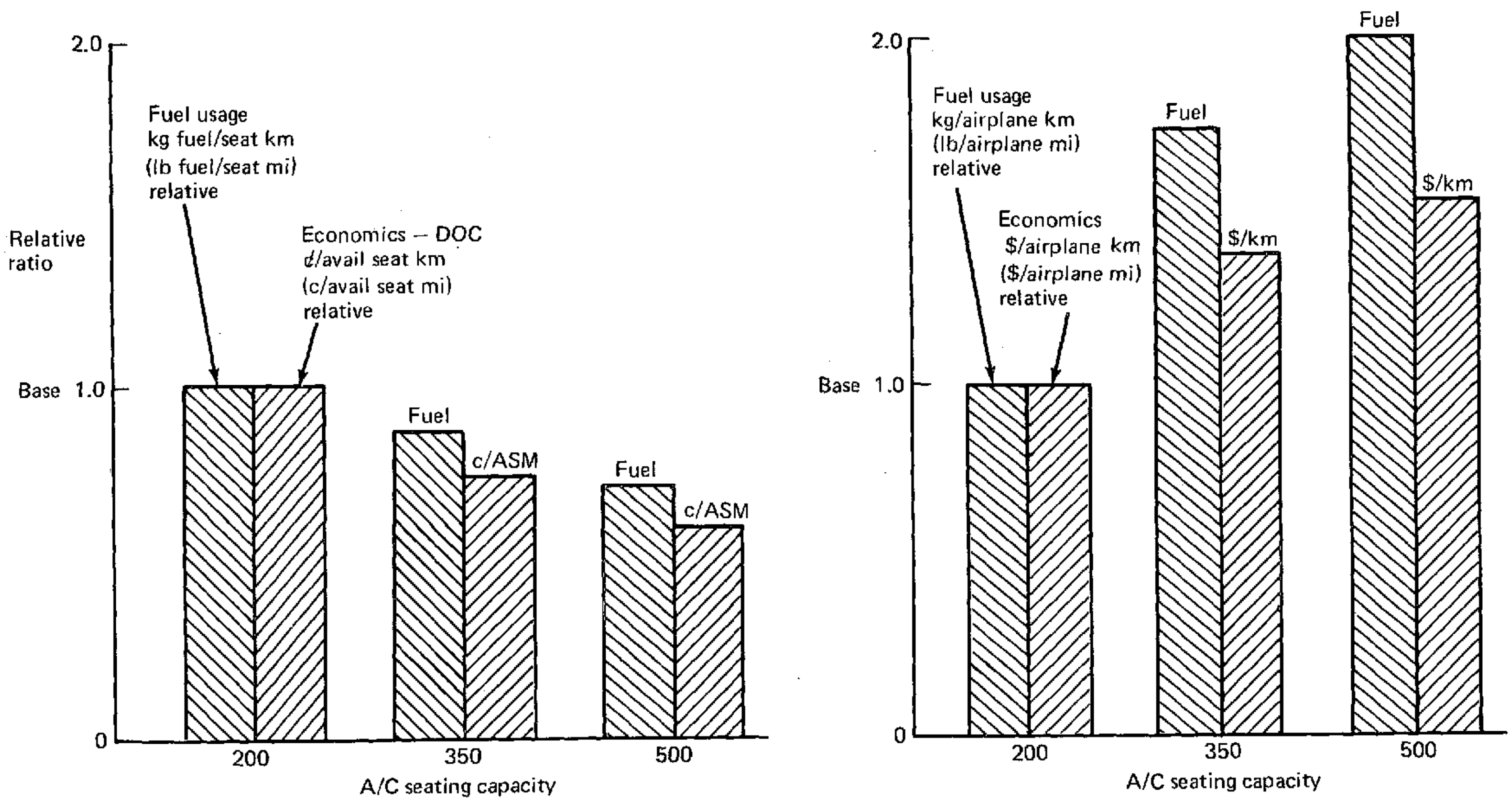


Figure 80.—Performance Summary

is great potential available for fuel saving, economical operation would exist only, therefore, if airplane capacity can be matched to the demand for service.

4.7.5 FREQUENCY/PAYLOAD VERSUS CONGESTION AND FUEL USE

In the past, competitive pressures have forced airlines to meet demand by increasing frequency. Figure 81 indicates the congestion impact at the major airports if traffic increases by the factors of 2.2 or 3.2 (case I and case II) are accommodated by increased frequency only. The same chart shows significant increases in total fuel use and an increase in fuel per passenger due to increased delay.

The Federal Energy Office has been encouraging higher load factors, which in itself restricts frequency as a means of conserving fuel. The dotted lines on figure 81 show the effect of holding frequency down by allowing load factors to increase from 60% to 70% before new flights are added. Positive effects result in terms of the beneficial effect of reducing congestion at the major airports. Congestion with fuel penalties would still be present but to a lesser degree. Fuel usage would increase for both case I and case II, but the increase would not be as great as if load factors were held to 60%. Fuel per passenger decreases. Estimates based on past airline experience show that the number of "turnaways" is increased threefold, indicating a reduced quality of service. While higher load factors are undoubtedly a step in the right direction, this policy would not alone solve the congestion or fuel conservation if significant increases in passenger demand are considered.

4.7.6 AIRPLANE SIZE VERSUS FUEL-USE TRENDS

The payload study was directed toward matching aircraft size to routes, as well as to permit load factors to increase to the point where turnaways were becoming too frequent to be economically feasible for the airline. This condition was assumed to exist when the value of lost revenue equaled the additional costs of a larger airplane. Calculations were made with three sizes of aircraft, disregarding the aircraft presently in the American Airlines fleet currently serving the example route system. The results of this study are shown in figures 82 and 83.

For the case I (2.2 x 1973 traffic) conditions, it was found that a 70% increase in the average size of aircraft combined with a 67% load factor produced the best mix (profitability and fuel burned). This was based on the assumption that the frequencies estimated by American Airlines were the minimum necessary to service the routes studied. This number was almost equal to the number being flown in 1973. The results are shown at point A in figures 82 and 83. The fuel per passenger was 67% that of 1973 because of a higher (67%)load factor and larger aircraft. Profitability and level of service were found to be acceptable.

For the case II (3.2 x 1973 traffic) condition, average aircraft capacity was found to increase by over 270% compared to current fleet averages, as shown by point B in figure 82. Fuel per passenger reduced to 60% of current usage at a load factor of 67%.

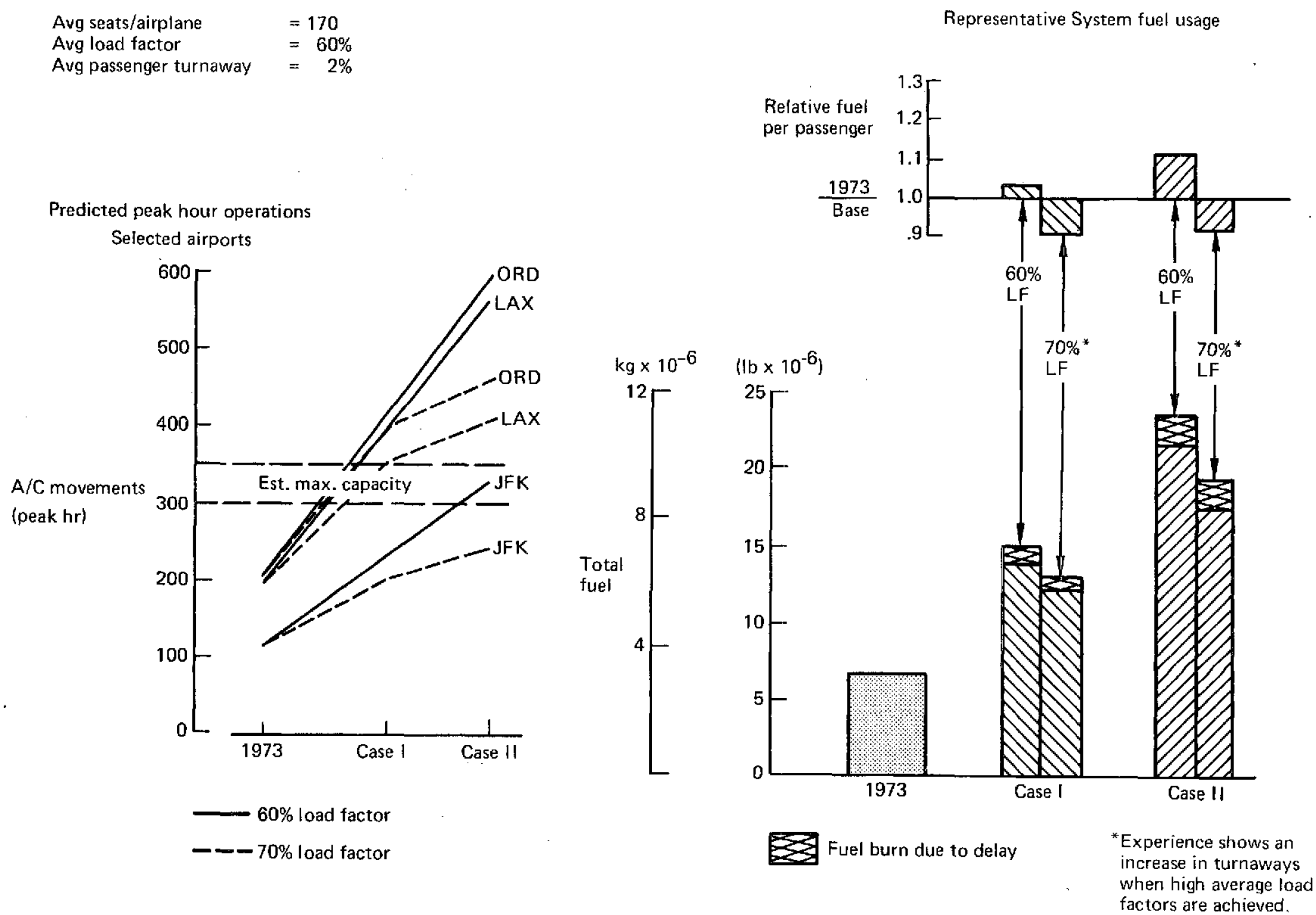


Figure 81.—Increased Frequency Projection

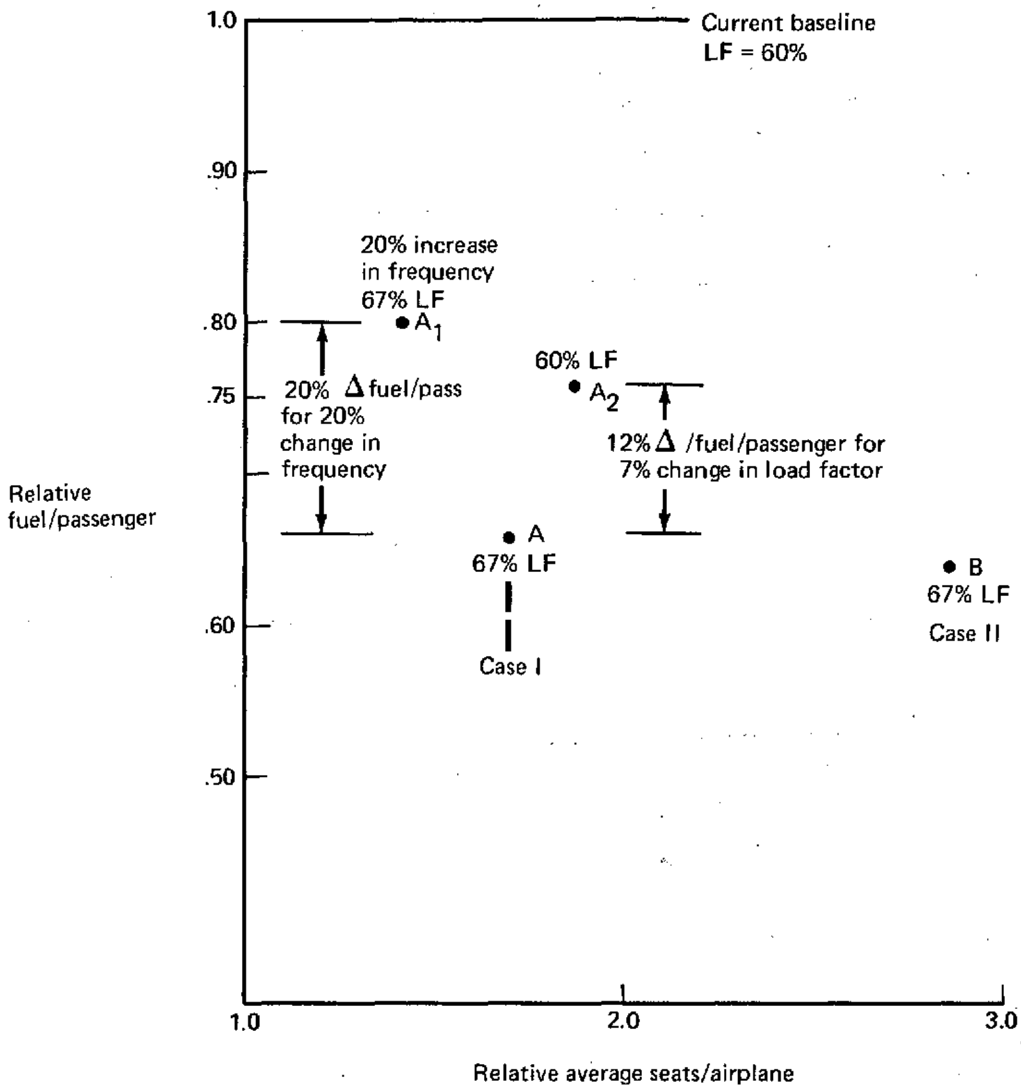


Figure 82.—Fuel Burn Versus Airplane Size

4.7.7 FREQUENCY AND LOAD FACTOR VARIATIONS

To determine the effect of independently varying load factor or frequency on aircraft size and fuel use, two additional excursions were made from the optimum 67% load factor condition for case I only. The results are shown as points A_1 and A_2 in figures 82 and 83 and are described in the following paragraphs.

4.7.7.1 Fixed Load Factor, Variable Frequency (point A_1 in figs. 82 and 83)

By holding the load factor at the optimum 67% and allowing the frequency to expand by 20%, average aircraft capacity was decreased significantly. Fuel use increased by 20% (fig. 82) while profitability decreased to 75% of the optimum case I baseline (fig. 83).

4.7.7.2 Fixed Frequency, Variable Load Factor (point A_2 in figs. 82 and 83)

Assuming the load factor deteriorated to 60% while holding the frequency constant, average aircraft capacity increased and fuel use increased by 12% (fig. 82). Relative profitability decreased by 6% (fig. 83). It may be concluded that larger aircraft with concurrent restricted frequency would yield great influence on fuel consumption and airline profitability. Higher load factors are a step in the right direction and should be encouraged. However, the leverage of higher load factor is not as great as that of restricted frequency and would result in a lower level of passenger service if carried too far.

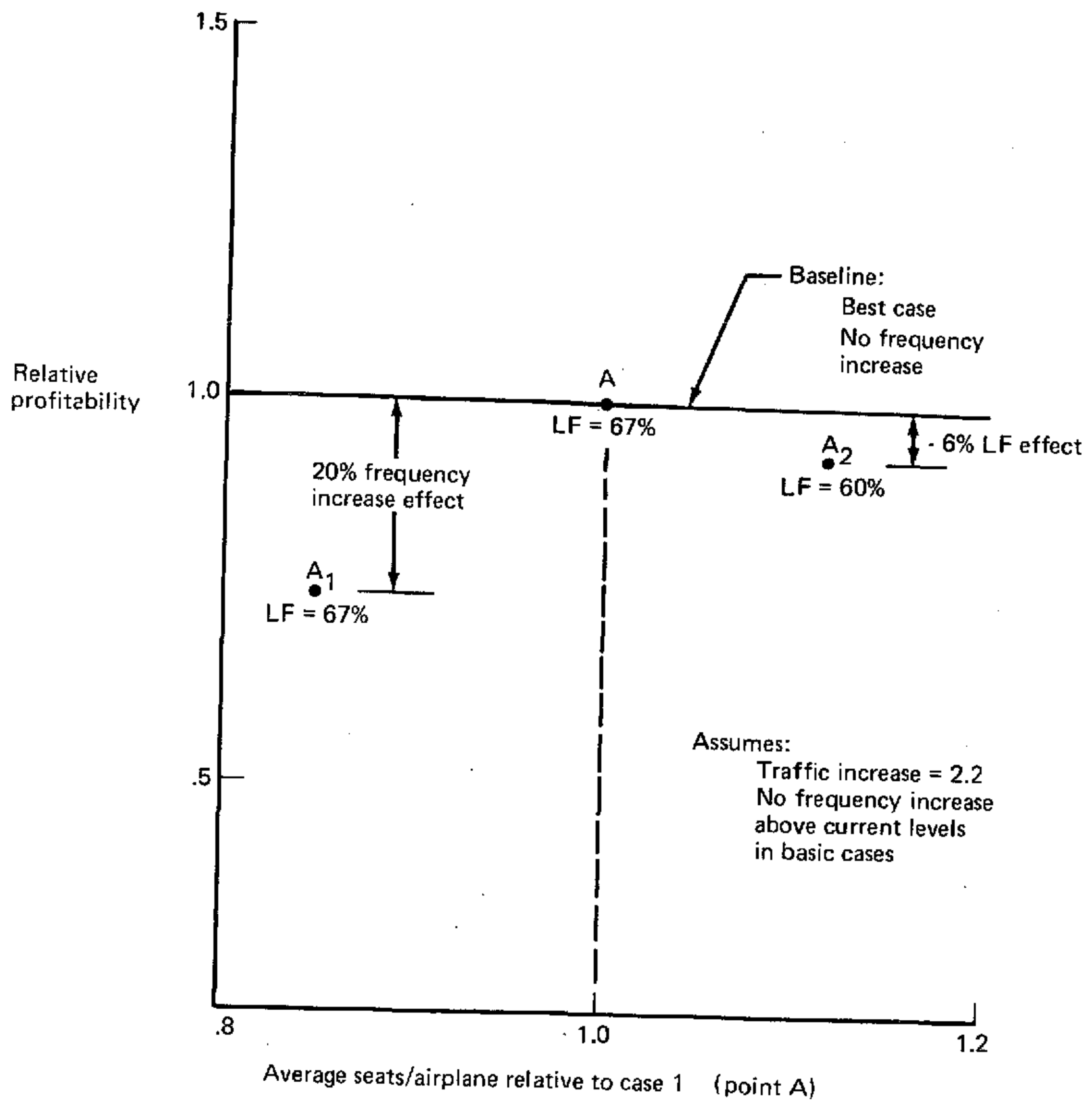


Figure 83.–Profitability Versus Aircraft Size

4.8 SENSITIVITY STUDY ECONOMIC EVALUATION PROCEDURE

Economics for the sensitivity studies were evaluated on the basis of the 1974 update of the ATA formula. No attempts were made to incorporate results of specialized studies that departed from the standard formula approach during the sensitivity study phase of the program. This method was considered adequate and desirable for this stage of the analysis for the following reasons:

1. The economic analysis for the sensitivity studies was for the purpose of determining the relative costs or relative benefits of each point within the variable tested. The objective was to determine if one point in a set was better or worse than the other points in that set. The absolute magnitude of the values, while believed to be reasonably accurate, was of little or no interest at this point in the study. The incremental effect on airline economics of a particular fuel conserving feature was the objective of the analysis.

2. The sensitivity studies were made on a present day technology aluminum aircraft. The ATA formula reproduces present day experience of airlines in general with a reasonable degree of accuracy, since the formulas are simply curve fits to plots of reported data for operating airlines. The aircraft price input to the ATA formula calculations was derived from contractor experience.

3. The nature of the sensitivity studies with many variables and several points within each variable made it impossible to make a more detailed study for each case even if it were desirable to do so.

Each of the sensitivity studies reported herein includes the economic results in that section. Other than in a few cases where it was desirable to see the effect of doubling the fuel price, calculations were made at fuel prices of 5.8¢/liter (22¢/gal) and 7.9¢/liter (30¢/gal). Both are shown in the results for the various sensitivity studies. Economics were evaluated at average airline conditions of 1852-km (1000-nmi) stage length and 55% load factor.

Return on investment (ROI) was also calculated in each of the sensitivity study areas. In each case the ROI and DOC followed the same trend. This is due to the small differences in aircraft price resulting from aircraft differences investigated in the sensitivity studies. Utilization calculated by airline methods will not vary greatly because of a small change in cruise velocity. Whenever investment and utilization are approximately equal, the aircraft with the lower operating cost will have the higher ROI. Therefore, ROI results have not been presented.

5.0 TERMINAL AREA COMPATIBILITY (TAC) FEATURES

5.1 INTRODUCTION

During the previous TAC study (ref. 2), eight features were defined which appreciably improved the terminal area compatibility of the baseline airplane. These are listed in the first column of table 13. In order to isolate energy considerations from terminal area compatibility, each sensitivity study was performed with the TAC features excluded. At the conclusion of the sensitivity studies, these features were reexamined in the light of their interaction with low-energy modifications and any new technical information affecting them. Recommendations were then made for the best form of each TAC feature for the TAC/Energy configuration to be defined during the next study phase. These recommendations are also summarized in table 13.

Four TAC features were still deemed appropriate without modification. These were the increased ground deceleration capability and the high-speed turnoff capability for decreasing congestion, the improved engine pollution technology for emission reduction, and the advanced avionics system for operational reduction of noise and congestion. The other four features are discussed in the following paragraphs.

5.2 WING TRAILING VORTEX MODIFICATION

At the time of the reference 2 study, the only available approach to wing trailing vortex reduction involved positioning of the outboard engines near the wingtips, for vortex reduction during takeoff, and deployment of vortex dissipator devices during approach. During the ensuing period, NASA studies and tests have indicated that proper scheduling of the trailing-edge flaps to modify the spanwise lift distribution potentially provides an effective technique. This method also imposes fewer energy penalties than the earlier recommendation. Alternatives currently under consideration are shown in table 14.

5.3 LOW-SPEED APPROACH AND HIGH TAKEOFF GRADIENT

The previous TAC studies indicated that both the low approach speed (which is desirable for congestion reduction) and a steeper takeoff gradient for noise reduction could be achieved by increasing the wing aspect ratio to 9 and increasing engine size for added takeoff thrust. A bonus of reduced energy consumption was noted at that time. The sensitivity studies indicated that, for further energy reduction, a further increase in aspect ratio to a value of 12 is optimum and would provide the desired landing speed and takeoff gradient.

5.4 STEEP DESCENT CAPABILITY

To minimize the approach noise footprint area, the TAC airplane was configured to allow very steep (9°/3°) descents with very low thrust settings. This involved the addition of drag brakes and the provision of two large, in-flight operable APU's to provide anti-icing capability at the low engine thrust settings. The same APU's were to be used to operate powered wheels for ground taxi and to minimize ground emissions, noise, and fuel consumption. This combination imposed appreciable penalties in weight (and hence fuel

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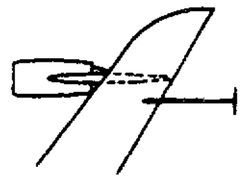
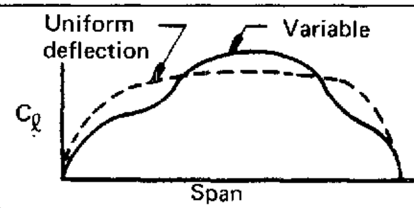
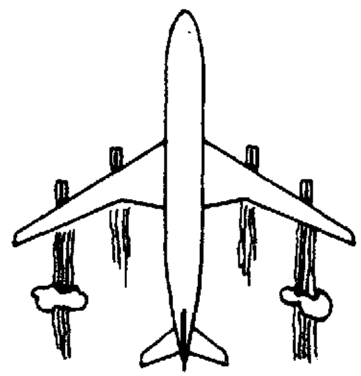
Table 13.—Terminal Area Features

Terminal area compatibility feature	Area of improvement	Design approach		Reason
		TAC airplane	TAC/Energy airplane	
Wing trailing vortex modification 1.61–4.83 km (1 to 3 mile) separation	Congestion	• Outboard engines • Vortex dissipators	• Trailing-edge flap scheduling	NASA flight test results (preliminary)
Low-speed aerodynamic improvement approach speed 222 km/hr (120 kn) 8-10° T.O. gradient	Congestion noise	• Aspect ratio 9.0 • Adequate T.O. thrust	• Aspect ratio 12 sweep 25° • Adequate T.O. thrust	Reduced energy use
Increased ground deceleration capability 2.75-3.66 m/sec^2 (9-12 ft/sec^2)	Congestion	• 2.75 m/sec^2 (9 ft/sec^2) • Increased brake size • Automated braking system	Same	Adequate
High-speed turnoff 74-111 km/hr (40-60 kn)	Congestion	• 74-111 km/hr • (40-60 kn) Noise wheel loading	Same	Adequate

Table 13.—(Concluded)

Terminal area compatibility feature	Area of improvement	Design approach: TAC airplane	Design approach: TAC/Energy airplane	Reason
Steep descent capability (9° to 12°)	Noise	● 2 segment approach $9^o/3^o$; 2 rings— 1 splitter ● Drag brakes ● Minimum thrust	To be determined	● Minimize fuel use
Powered wheel/ secondary power system modifications	Emissions noise	● Flight-critical APU (2) - powered wheels - anti-icing	● Ground APU (1) - powered wheels ● Engine bleed & lower glide slope when anti-icing required	● Reduced APU maintainability impact
Improved pollution technology Goal: CO(IDLE) 20 kg/1000 kg HC (IDLE) 4 NO_x (T.O.) 10	Emissions	● Advanced combustor OPR 24 35 kg/1000 kg 6 12 (also powered wheels)	Same	● Adequate
Avionics systems	Congestion noise	Modified ATT provisions	Same	● Adequate

Table 14.—Vortex Suppression Candidates

Concept		Performance impact	Status
Outbd engine location and vortex dissipator		1. Structural weight increase due to flutter 2. Increase in cruise drag	1. Undesirable weight penalties 2. Dissipator not effective
Variation in spanwise TE flap deflection		1. Possible increase in landing speeds at sweep 30°	1. NASA/FRC flight test data indicate 3.70-5.56 km (2-3 nmi) separation possible by retracting outbd flaps
Variation in spanwise thrust distribution		1. Increased engine size for takeoff 2. Increased noise on landing approach	1. NASA/LRC wind tunnel data and FRC flight data currently inconclusive
Winglets		1. Potential reduction in cruise drag 2. Possible increase in wing weight	1. NASA/LRC data indicates reduction in cruise drag 2. Effect on vortex strength to be determined 3. Effect on load distribution to be determined

consumption) and maintenance costs. For the fuel-conservative configuration, the APU number and size were reduced to one APU adequate for powered-wheel operation, and the drag brakes were eliminated. Maintaining the low noise levels during approach of the TAC/Energy airplane would impose an appreciable energy penalty, and designing the airplane to maintain the same low noise levels under infrequent icing conditions would cause additional energy expenditure on all flights. The final combination of approach flightpath angle, engine noise treatment, noise footprint, and procedural avoidance of icing was, therefore, left to be decided during the detailed configuration of the TAC/Energy airplane, when the more general trade between energy and overall noise patterns could be made. The basic criterion to be followed during the general trade would be to define the highest two-segment approach capability of the candidate TAC/Energy airplane and to determine the resulting noise footprint characteristics using peripheral lining only in the engine nacelles. This criterion would thereby yield the minimum noise and minimum energy combination. The weight, performance, fuel use, and economic penalty with additional noise attenuation could then be identified as a trade between the cost in fuel use versus noise reduction.

6.0 FINAL AIRPLANE CONCEPT DEFINITION AND ASSESSMENT

6.1 AIRCRAFT DEFINITION

As shown by the study logic diagram (fig. 7), the latter part of the study was devoted to the following activities:

- Definition of a candidate TAC/Energy aircraft concept that incorporated key fuel conservation features as identified during the sensitivity studies, as well as the terminal area compatibility features that were previously identified during the TAC study (ref. 2)

- Assessment of the technical and economic characteristics of the candidate TAC/Energy concept (with emphasis on fuel use) and the comparison with other current and advanced aircraft concepts

- Definition of recommended research and technology programs needed to support decisions to commit desirable fuel conservation features to future transport programs

This section describes the results of the first two activities. The third is covered by section 8.0, Research and Technology Recommendations.

Four 18 140-kg (40 000-lb) payload, 5556-km (3000-nmi) range aircraft concepts were used for the preceding activities—the TAC/Energy and three comparison concepts which are variations of configurations that were defined previously during the TAC study (ref. 2). The characteristics of the four concepts are shown in table 15, which covers both the original and modified versions of the three used for comparison during this study. A summarized explanation of the information contained in that figure follows for each of the four concepts:

1. Current Wide Body (CWB-E)—incorporates aluminum structure and other technology consistent with current wide-body transport design. Performance of the three-engine concept in this study was based on cruise speed of M = 0.82 for a long-range cruise, as contrasted to the CWB version used during the TAC study, which was based on minimum DOC cruise Mach number (M = 0.85).

2. Advanced Transport Technology (ATT-E)—incorporates advanced structures and propulsion together with a full-time flight-critical stability augmentation system consistent with a 1985 operational introduction. Performance of this three-engine concept was based on the contractor's latest aerodynamic data base and long-range cruise speed (M = 0.88) as contrasted to the ATT concept in the TAC study, which was based on the data base developed in the 1970-72 time period and the minimum DOC Mach cruise speed of 0.90.

3. Terminal Area Compatibility (TAC-E)—characteristics and performance are the same as the ATT-E in item 2, except the concept includes special provisions for reduction of

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Table 15.—TAC/Energy and Comparison Aircraft Concept/Characteristics Definition

Concept / Definition	1. Current wide body		2. Advanced transport technology		3. Terminal area compatibility		4. TAC/Energy
	1973 CWB (reference)	1974 CWB-E	1972 ATT (reference)	1974 ATT-E	1973 TAC (reference)	1974 TAC-E	
Cruise speed for performance evaluation	M_{CRIT} 0.85	M_{LRC} 0.82	M_{CRIT} 0.90	M_{LRC} 0.88	M_{CRIT} 0.90	M_{LRC} 0.88	M_{LRC} 0.80
Aerodynamic data base	1965-67	1965-67	1970-72	1974	1970-72	1974	1974
Detail definition source	NASA CR-132367	NASA CR-132367 plus sec. 6.1.2	NASA CR-112092	NASA CR-112092 plus sec 6.1.2	NASA CR-132367	NASA CR-132367 plus sec. 6.1.2	Sec. 6.1.1
Technology characteristics and features	Current wide body		• Advanced structure • Full-time stability augmentation system • Advanced propulsion		• Advanced structure • Full-time stability augmentation system • Advanced propulsion PLUS Terminal area compatibility		• Advanced structure • Full-time stability augmentation system • Advanced propulsion PLUS Terminal area compatibility and fuel conservation features

congestion, noise, and emissions to enhance terminal area compatibility, which required changing from a three-engine to a four-engine concept.

4. TAC/Energy Concept (TAC/Energy)—the prime subject of this study—an $M = 0.8$ (at long-range cruise) configuration that incorporates desirable wing geometry and propulsion and systems features to enhance fuel conservation, in addition to terminal area compatibility features consistent with the TAC study (ref. 2). The same technology is included as the ATT-E and TAC-E configurations. Performance is based on using an advanced airfoil designed for the region of $M = 0.8$ and long-range cruise speed.

It can be seen from table 15 that the redefinition of the performance of the three comparison concepts was necessary to provide a consistent base for that comparison. This reevaluation took into account the aerodynamic data base and/or cruise speed differences noted in the two columns under each concept heading. By doing so, the "E" version of each concept was given the benefit of the latest data and methods of operation that would enhance fuel use characteristics. A fair comparison with the TAC/Energy configuration results.

The preceding discussion shows that the TAC/Energy airplane concept of this study was configured with fuel economy being the prime objective, whereas minimum cost was the sizing criterion for the CWB and ATT concepts, and low noise, emissions, and delay were the prime sizing criteria for the TAC concept defined during the previous TAC study. To compare the airplanes of the two studies on a consistent basis, it was necessary to update the three previously defined concepts. The CWB airplane, which used conventional technology, was updated by using long-range cruise procedures and sized for minimum fuel usage. The updating of the TAC and ATT airplanes included using long-range cruise procedures, sizing for minimum fuel usage, plus changing the advanced technology aerodynamics to a contractor-advanced airfoil basis and revising the propulsion weights to a current advanced technology base.

An alternate way of evaluating the CWB airplane is to use long-range cruise procedures but not to resize the wing area and engine thrust to take advantage of the increased range. This is representative of what would occur on a current airplane as opposed to a new airplane designed for long-range cruise (CWB at LRC).

6.1.1 TAC/ENERGY CONCEPT

Based on the results of the sensitivity studies, the contractor recommended to NASA that the candidate TAC/Energy concept should be developed to the following key requirements that would minimize fuel usage:

- Long-range cruise Mach number, 0.8
- Design range, 5556 km (3000 nmi)
- Aspect ratio, 12

- Wing sweep, 25°(quarter chord)
- Wing thickness, 8% (outboard)
- Turbofan bypass ratio, 6.0
- Climb speed, 154 m/s (300 kn)
- Cruise altitude, 9144 m (30 000 ft) minimum with a single 1219-m (4000-ft) step climb
- Air-conditioning system, engine bleed/vapor cycle with 50% recirculation

Although aircraft larger than the 18 140-kg (40 000-lb) payload capacity showed significant gains in fuel use per seat mile, it was recommended that the same payload be maintained so that a consistent base for comparison of fuel usage would be present. It was also required that the TAC/Energy concept include features that would enhance terminal area compatibility. Recommendations in this respect are described in section 5.0 for all features except the steep (9°/3°) approach concept used for approach noise reduction during the TAC study. It was recommended that methods to be employed for this area be left open until the TAC/Energy concept definition was underway so the implications on the specific configuration could be evaluated. All these recommendations were approved by NASA.

With respect to approach noise reduction, the impact of the methods used during the reference 2 study were reviewed in light of the objectives of this study (minimum fuel use) and the configuration impact. The method employed on the previous TAC concept was based on a 9°/3° two-segment approach. That method required addition of large drag brakes on the aft fuselage at a cost of 500 kg (1100 lb) and considerable complexity. In addition, it was required that the engines be throttled to the idle position—a condition that would not allow sufficient engine bleed for anti-icing. This resulted in the addition of two large flight-critical APU's at a cost of 1280 kg (2920 lb) and additional complexity. It was determined that a similar impact would result on the TAC/Energy concept and the implications to fuel reduction objectives would be unreasonable.

Review of the glide slope capability of the TAC/Energy concept indicated that a 6°/3° glide slope could be maintained without special drag brakes and with sufficient engine throttle to maintain anti-icing requirements. It was also determined that addition of rings and splitters could be provided to lower the approach noise, if necessary. To meet the objective of minimum fuel, the decision was made, therefore, to determine the noise and fuel use characteristics following a concept that used a 6°/3° glide slope with peripheral treatment only in the engine nacelles. The impact of adding noise attenuation treatment would subsequently result in defining both the minimum fuel use design and the impact on fuel use for lower noise levels.

The preceding design requirements were, therefore, applied during the definition of the TAC/Energy concept. The procedure followed consisted of a three-step process: (1) an aluminum airplane with advanced propulsion was first defined, including the fuel conserving features; (2) the aluminum version was then altered to include advanced structure and full-time flight-critical stability augmentation; and (3) finally, the TAC features for reduced congestion, noise, and emissions were added. The TAC/Energy concept resulted. A brief description of the final TAC/Energy concept in each technology discipline is provided in the following paragraphs.

6.1.1.1 Configuration Description

The TAC/Energy configuration and geometric characteristics are shown in table 16 and figure 84.

Table 16.—TAC/Energy Airplane Geometric Characteristics

Weights, kg (lb)			
Gross weight	115 300 (254 200)		
Payload	18 140 (40 000)		
Operational empty weight	67 351 (148 480)		
Max fuel capacity	44 900 (99 000)		
C.G. limits, % MAC	22 fwd, 54 aft		
Powerplants			
Number	4		
Bypass ratio	6		
SLS thrust/engine	67 600 N (15 200 lb)		
Body			
Length	50.16 m (1 975 in.)		
Max diameter	5.24 m (206.5 in.)		
Accommodations	196 passengers—15% 1st, 85% tourist 10 LD-1 containers, 49 m^3 (1 730 ft^3)		
Landing gear, m (in.)			
Nose	(2)—0.86 x 0.25 (34 x 10)		
Main	(8)—1.22 x 0.35 (48 x 14)		
Truck size	1.80 x 0.94 (71 x 37)		
Oleo stroke (extended to static)	0.35 (14)		
Wing and empennage			
	Wing	Horizontal tail	Vertical tail
Area, m^2 (ft^2)	198.6 (2 138)	37.9 (408)	32.6 (350)
Aspect ratio	12	4	1.8
Taper ratio	0.25	0.4	0.3
c/4 sweep, deg	25	30	30
Incidence, deg	4	—	—
Dihedral, deg	5	0	—
t/c, %	14.5 to 8	8	8
MAC, m (in.)	4.56 (179.4)	3.27 (128.6)	4.66 (183.6)
Span, m (in.)	48.82 (1 922.1)	12.31 (484.5)	7.66 (301.4)
Tail arm, m (in.)	—	24.38 (959.8)	23.83 (938.2)
Tail vol coefficient	—	1.02	0.08

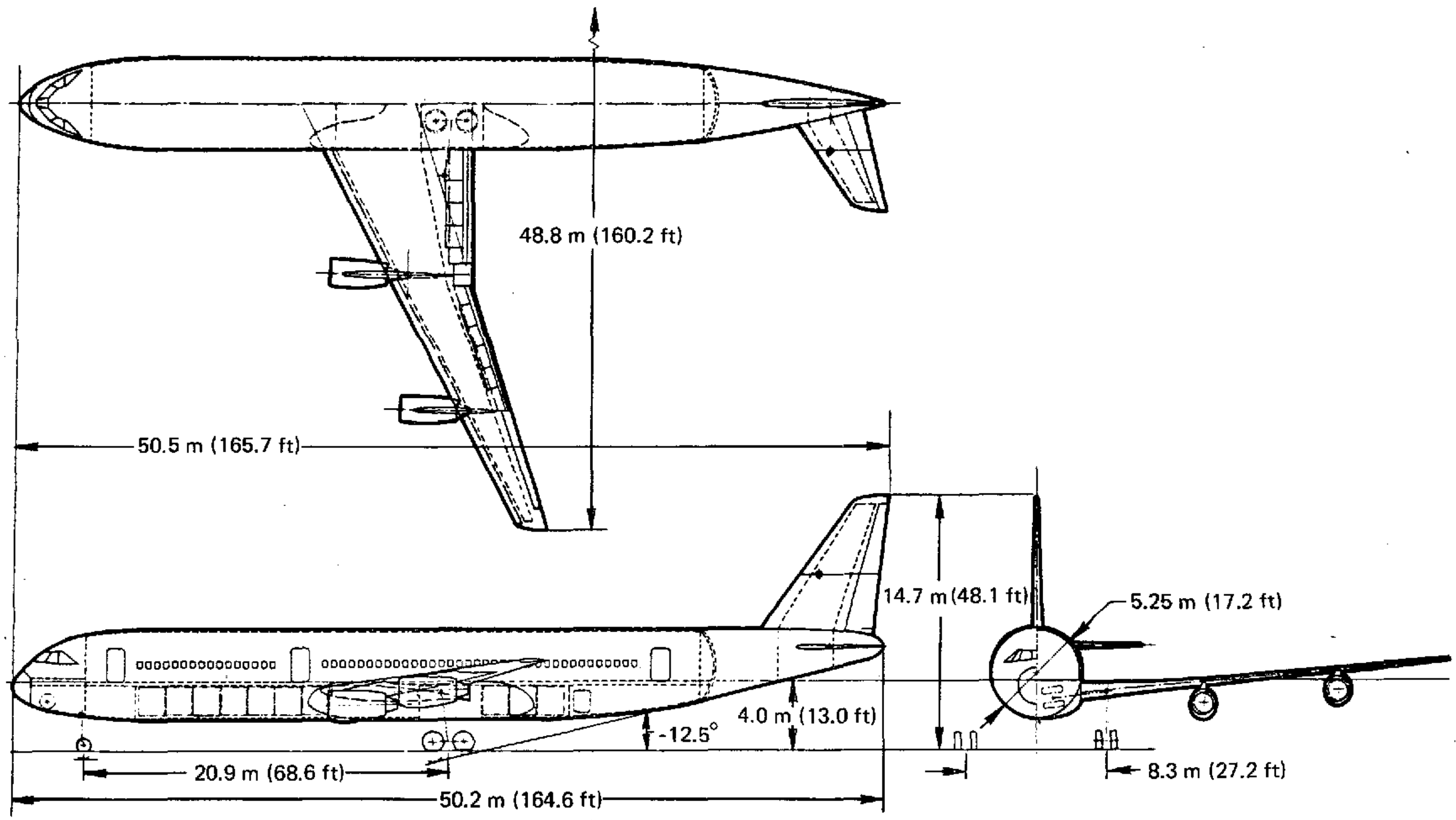


Figure 84.—General Arrangement, TAC/Energy Airplane

The passenger compartment is arranged with two aisles and a 15%/85% split between first class and tourist. Five-abreast 0.96-m (38-in.) pitch seating is provided in the first class section, with seven-abreast 0.86-m (34-in.) pitch seating in the tourist section, for a total of 196 seats. Provision is included for galleys, toilets, closets, and attendants' stations.

The fuselage diameter is 5.25 m (206.5 in.) and is 50.16 m (1975 in.) in length. All sections are circular from the cab bulkhead at STA 4.165 (164) to the rear pressure bulkhead at STA 39.522 (1556). The nose is designed for minimum drag with flat-pane windows meeting FAR visibility requirements for new aircraft. The volume under the floor is used for containerized and bulk cargo.

The wing, engines, and landing gear were arranged to satisfy several center-of-gravity and pitch-roll constraints. The wing MAC quarter chord was positioned on the body [at STA 22.606 (890)] to place the nominal aircraft c.g. in the center of the limits imposed by stability and control considerations. The main landing gear was located behind the aft c.g. limit and is of sufficient length to provide an aft-body pitch clearance of 12.5° at takeoff rotation. The wing dihedral of 5°, selected for stability and control considerations, gives adequate engine clearance for both static and dynamic cases.

The wing planform includes a straight trailing-edge fillet to provide adequate room for the inboard flap behind the landing gear trunnion (the landing gear oleo strut was slanted forward to minimize the size of the trailing-edge fillet). No area ruling was necessary due to the low cruise Mach number.

The landing gear tire and truck were sized to provide adequate flotation and room for the "powered-wheel" motors. This increased the gear bay size, with only a small impact on underfloor cargo volume. The gear was the only TAC feature that affected the external configuration.

6.1.1.2 Aerodynamic Technology

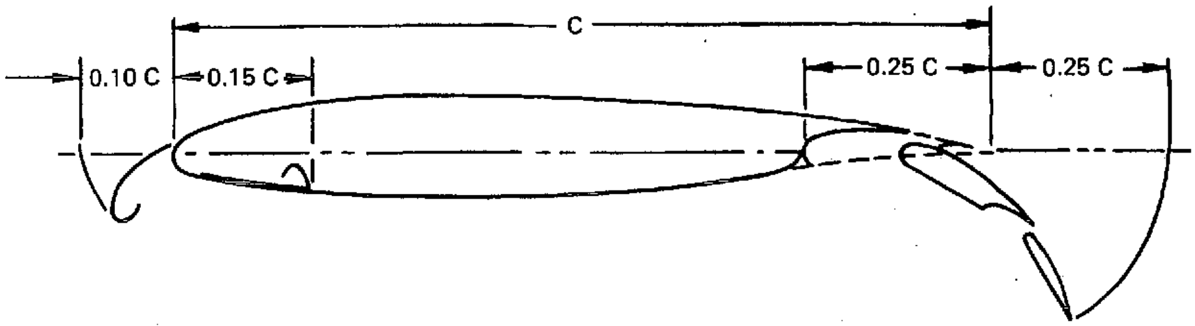
The low-speed aerodynamic data for the TAC/Energy airplane correspond to that used in the previous TAC study. A flap system schematic is shown in figure 85. The low-speed performance data correspond to this flap system which was adapted to the specific planform of the TAC/Energy concept for aspect ratio and sweep angle changes.

The high-speed drag polars used for the TAC/Energy airplane were developed using established methods based upon experience with subsonic jet airplanes. The basic airfoil characteristics are discussed in section 4.3.3.1. The advanced airfoil has essentially a non-peaky and aft-loaded type pressure distribution, which shows minimum shock losses at design, as well as off-design, conditions. The selected TAC/Energy airplane wing parameters were based on the sensitivity studies of section 4.3 (25° sweep, 8% thickness outboard, and aspect ratio 12.0).

6.1.1.3 Propulsion/Noise

Since the bypass ratio study showed the optimum bypass ratio (for minimum fuel usage and DOC) to be in the range of 5 to 7, the bypass-6 turbofan was selected as the engine for the

TAC TECHNOLOGY (ref. 2)



Leading edge
- Variable camber LE Krueger flap
- 10% local chord Fowler motion
- C_F/C = 15% local chord

Trailing edge
- Double slotted flaps
- 25% local chord Fowler motion
- Outboard flap span, $\eta \approx$ 0.74
- C_F/C = 25% local chord

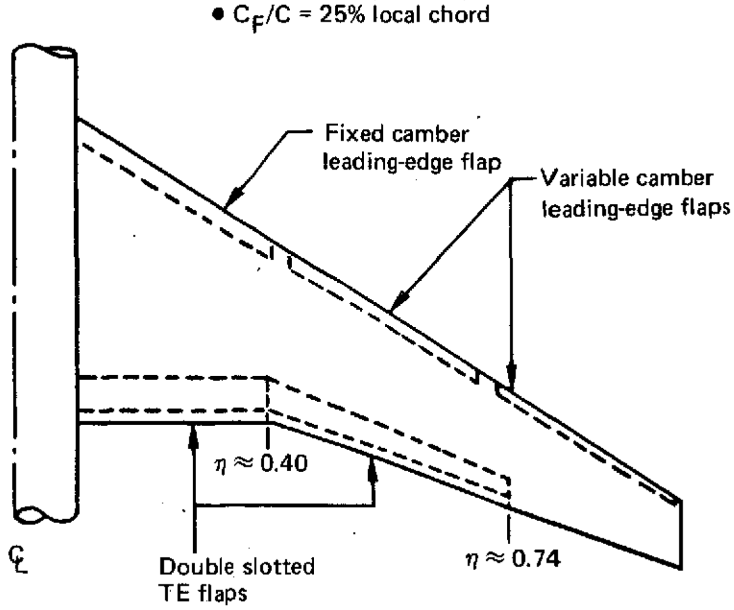


Figure 85.—Low-Speed Flap System Schematic

TAC/Energy airplane. This engine has the same OPR (24 to 1) and maximum turbine inlet temperature 1560 K (2800° R) as the engines used for the ATT and TAC studies. A BPR of 4 was selected for those studies because of the higher cruise speed. The bypass ratio study is discussed in more detail in section 4.4.2.

The engine selected for the TAC/Energy airplane has been quieted as much as possible consistent with fuel conservation objectives. The engine schematic shown in figure 86 includes acoustical treatment to quiet multiple pure tones, inlet, aft fan, and turbine noise components. The resulting configuration is dominated by inlet noise. Jet and core noise are substantially quieter than the suppressed inlet noise. Further quieting of the engine would require a longer inlet, inlet rings, or a sonic inlet. These additional features would, however, increase engine weight, reduce performance, and increase fuel consumption.

In figure 87 the flight profiles, takeoff and landing 90-EPNdB noise contours, and flyover noise levels are shown for the TAC/Energy airplane with four of the bypass 6, peripherally treated engines. Figure 87a shows the airplane with flaps at 17° capable of climbing to 400-m (1300-ft) altitude over the community noise measuring point 6500 m (3.5 nmi) from brake release.

The airplane produces 92 EPNdB with cutback and 94.5 EPNdB without cutback. During a 3° or 6°/3° approach, the airplane produces 102 EPNdB at the FAR 36 approach measurement point using the maximum flap deflection of 50°. Figure 88 shows that on a FAR 36 traded basis the airplane achieves a FAR 36 -5-EPNdB traded noise level.

Takeoff and landing 90-EPNdB noise contours are shown in figure 87b for half of the symmetrical contour. Takeoff at maximum TOGW closes the 90-EPNdB contour 9 km (≈ 5 nmi) from brake release. Contractor in-house studies showed that approximately 60% of the airports have communities closer in than 9 km and 65% have communities closer in than 10.7 km. (See fig. 87c.) Takeoff at average operational TOGW would shorten the takeoff noise contour.

During approach the 90-EPNdB noise contour closes 8.3 km (≈ 4.5 nmi) from the threshold for the 3°, flap 50° approach; 6.5 km (≈ 3.5 nmi) for the 3°, flap 30° approach; and 4.8 km (≈ 2.5 nmi) for the 6°/3° two-segment approach, About 70% of the airports have communities closer in than the 8.6-km distance, while about 50% of the airports have communities closer in than the 4.8-km distance from threshold. Consequently, the 6°/3° two-segment approach could be used at a substantial number of airports to reduce aircraft noise in the community.

The engine noise-thrust-altitude characteristics of the selected bypass-6 engine are shown in figure 89. These noise characteristics were used in estimating the aircraft engine noise. This was achieved by scaling the noise data for engine size and aircraft velocity. Arrows on the figure show the noise scaling required at cutback, approach, and sideline. Airframe noise is also shown for the approach noise curve for the TAC/Energy airplane approaching at 705 m/s (137 kn). The airplane engine noise is logarithmically added to the airframe noise to obtain the airplane noise. Figure 89 was obtained by suppressing the individual noise components shown to dominate in the hardwall (unsuppressed) engine noise estimates in figures 90 through 92.

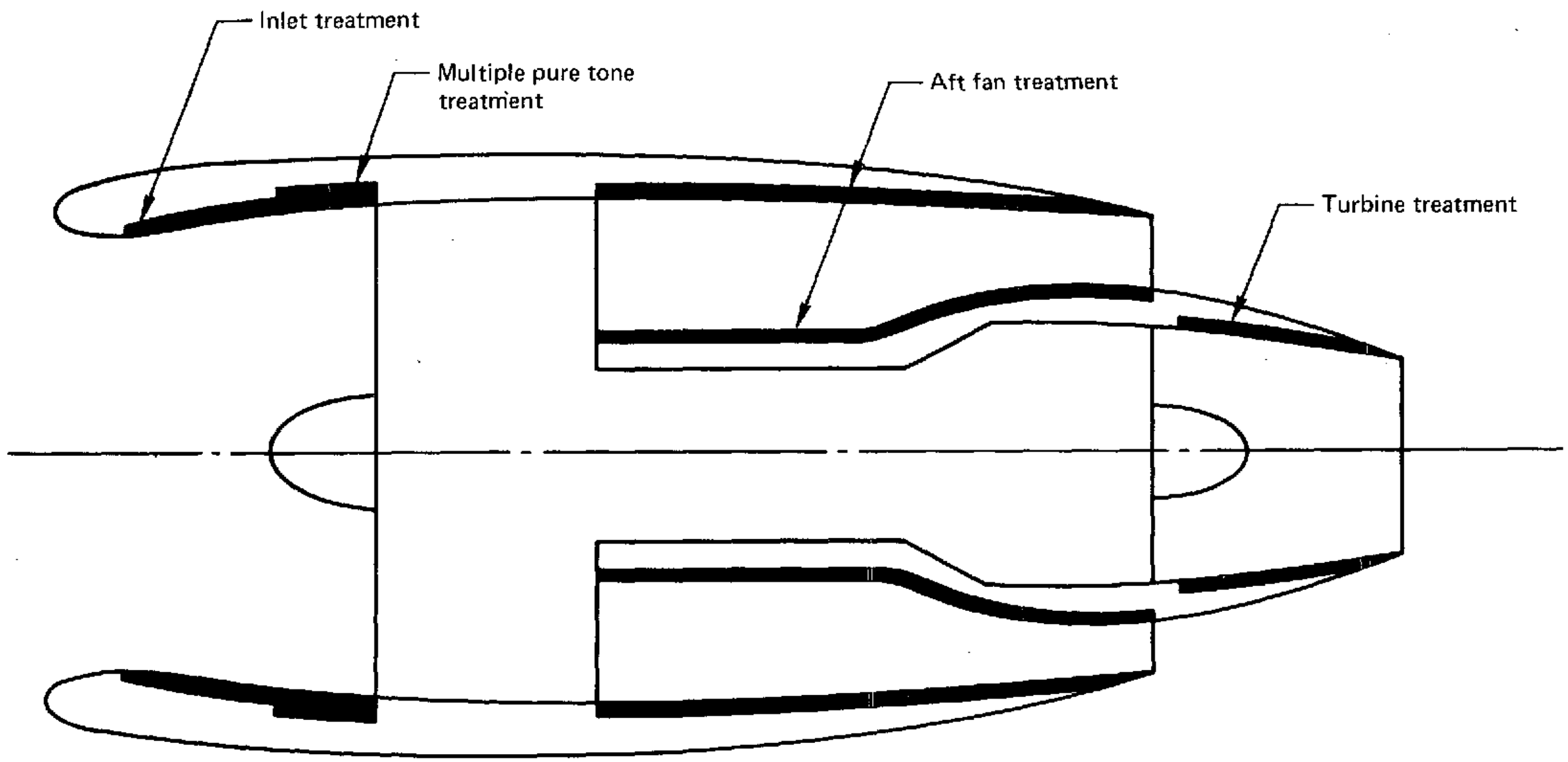


Figure 86.—Peripheral Treatment of Bypass 6 Engines

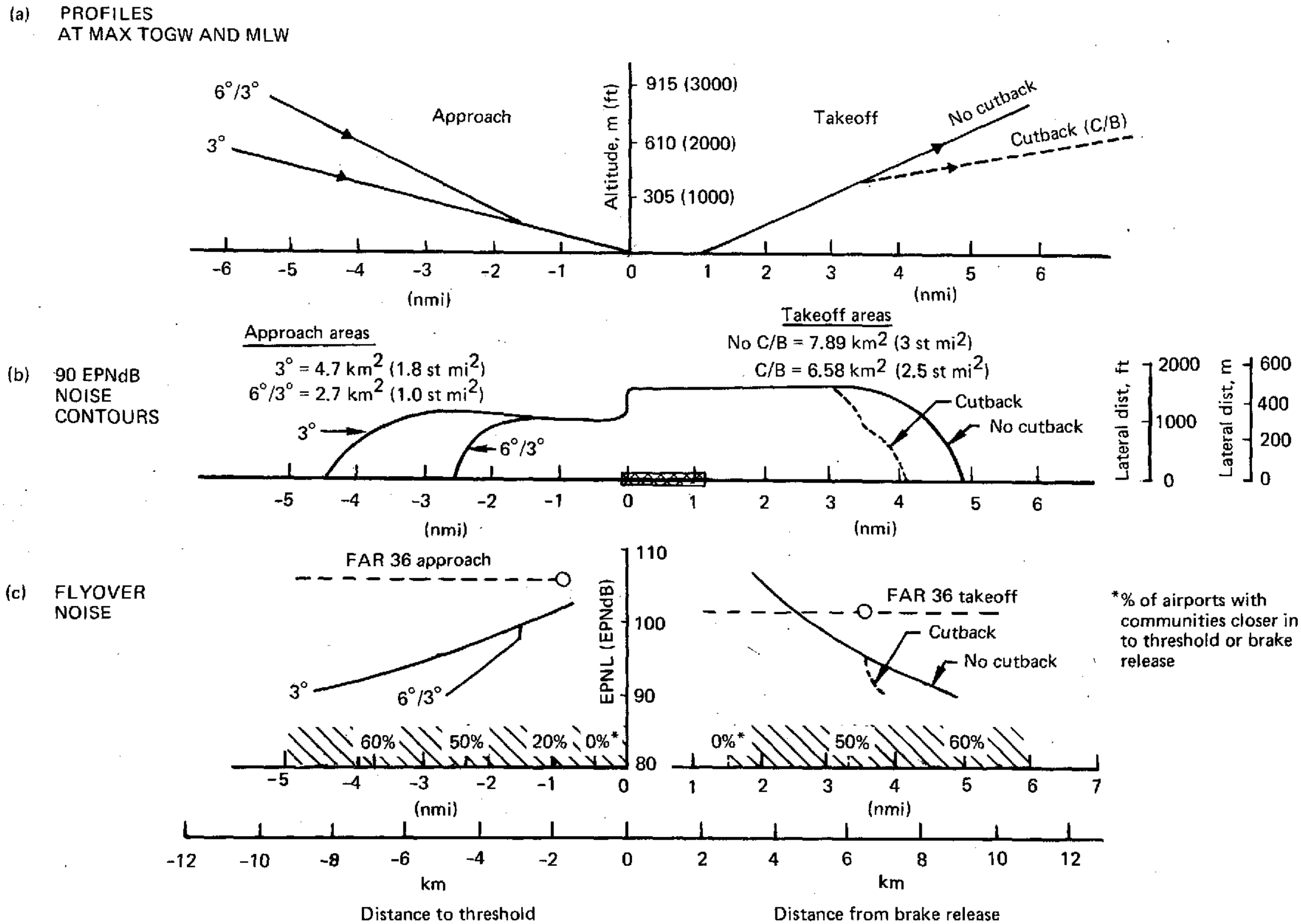


Figure 87.—Takeoff and Approach Noise, TAC/Energy Airplane

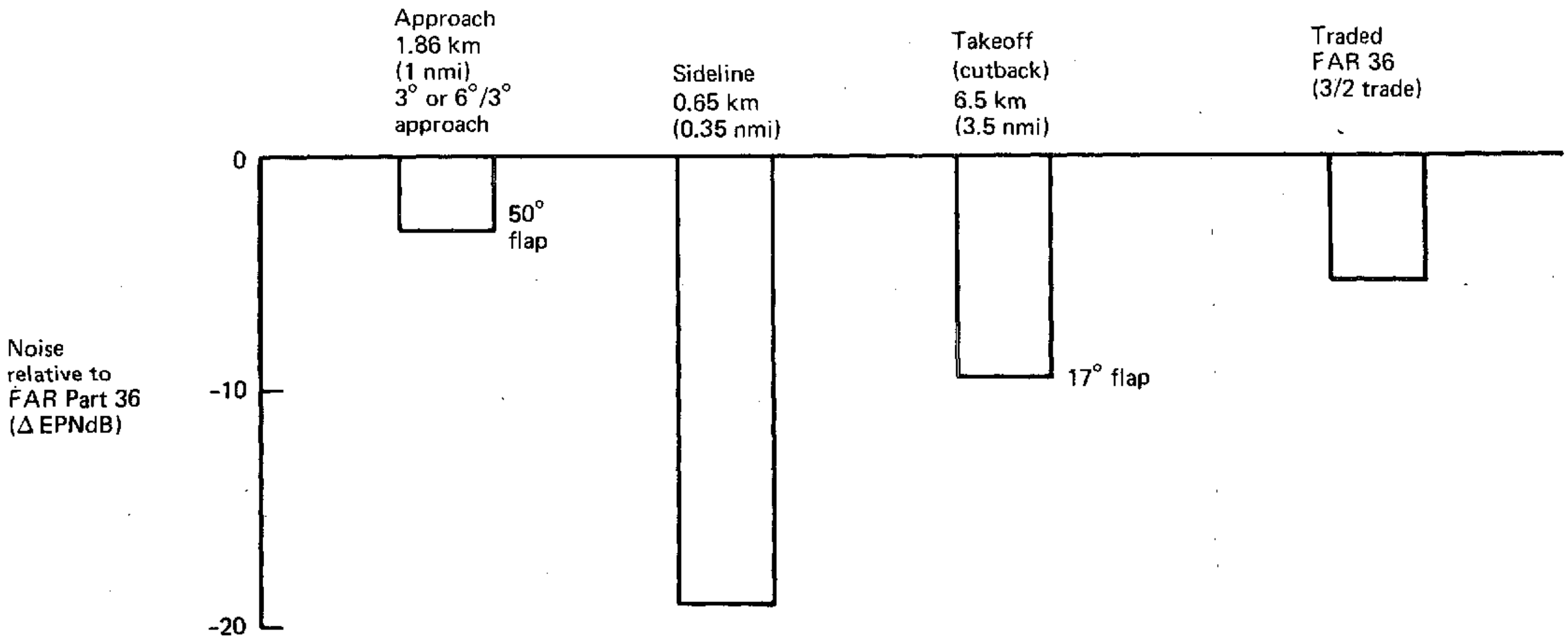


Figure 88.—TAC/Energy Noise Relative to FAR 36 (Peripheral Inlet and Fan Duct Treatment)

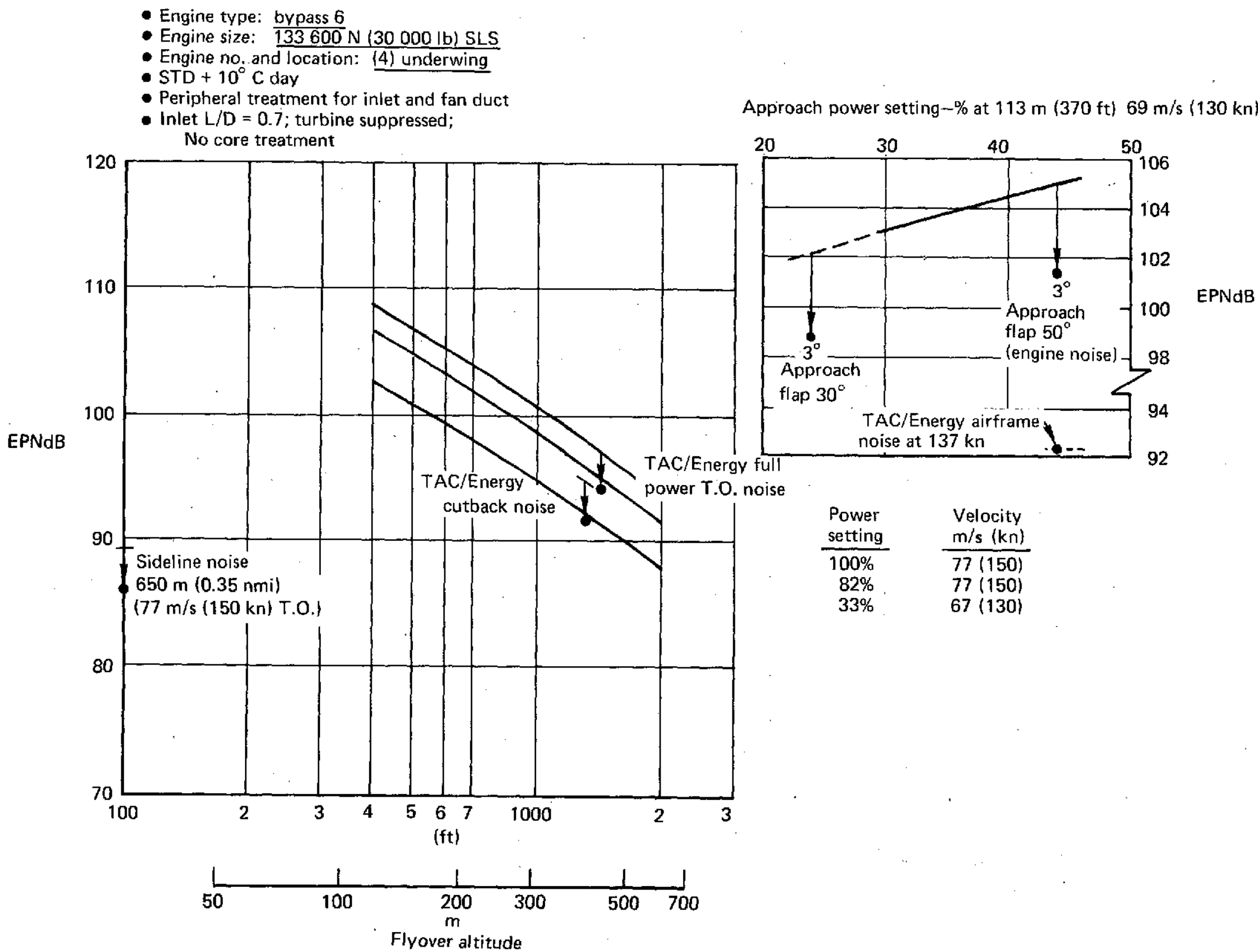


Figure 89.—Thrust-Altitude-Noise Estimate for Bypass 6 Engine (Inlet L/D = 0.7)

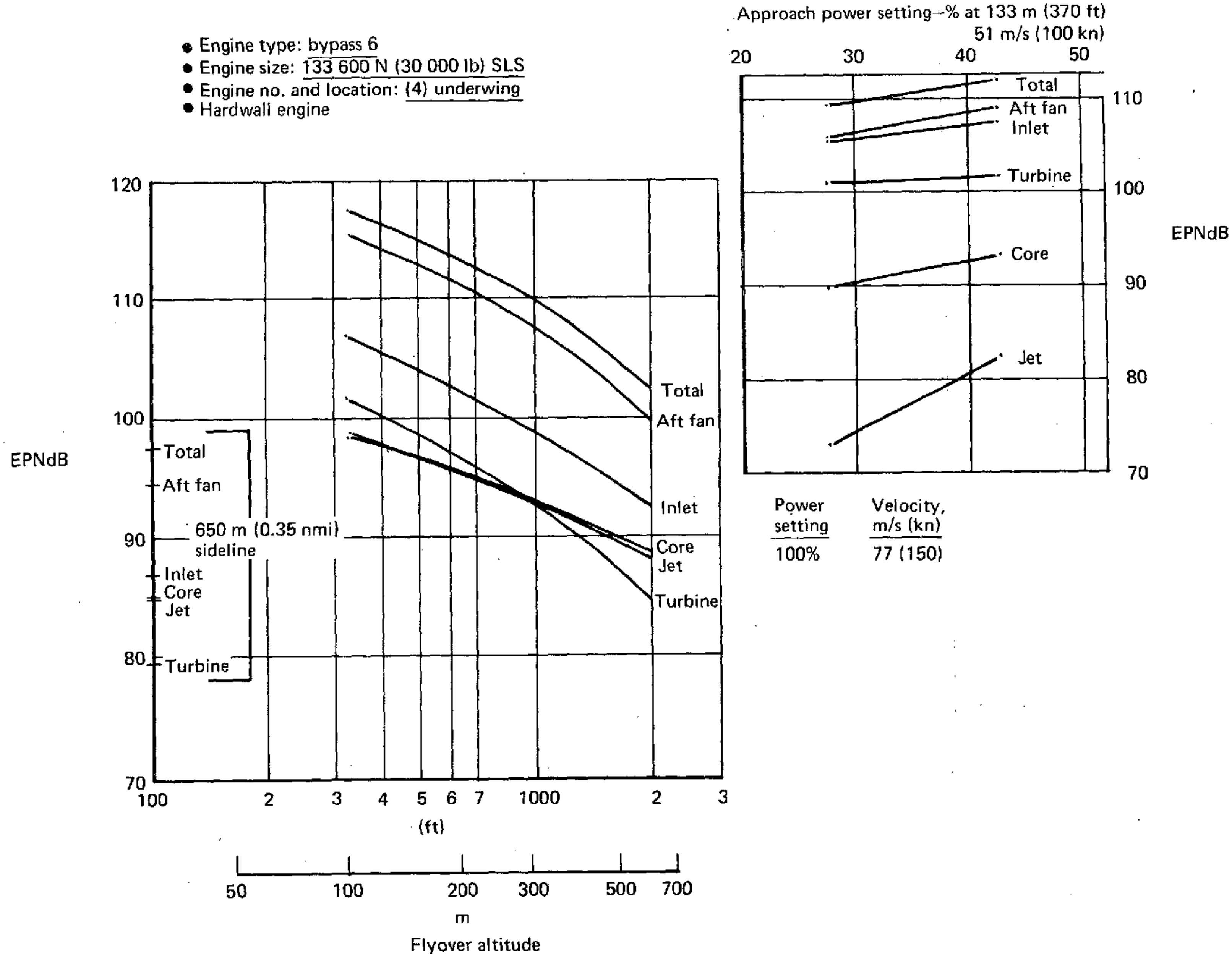


Figure 90.—Component Noise During Takeoff and Approach (Hardwall Bypass 6 Engine)

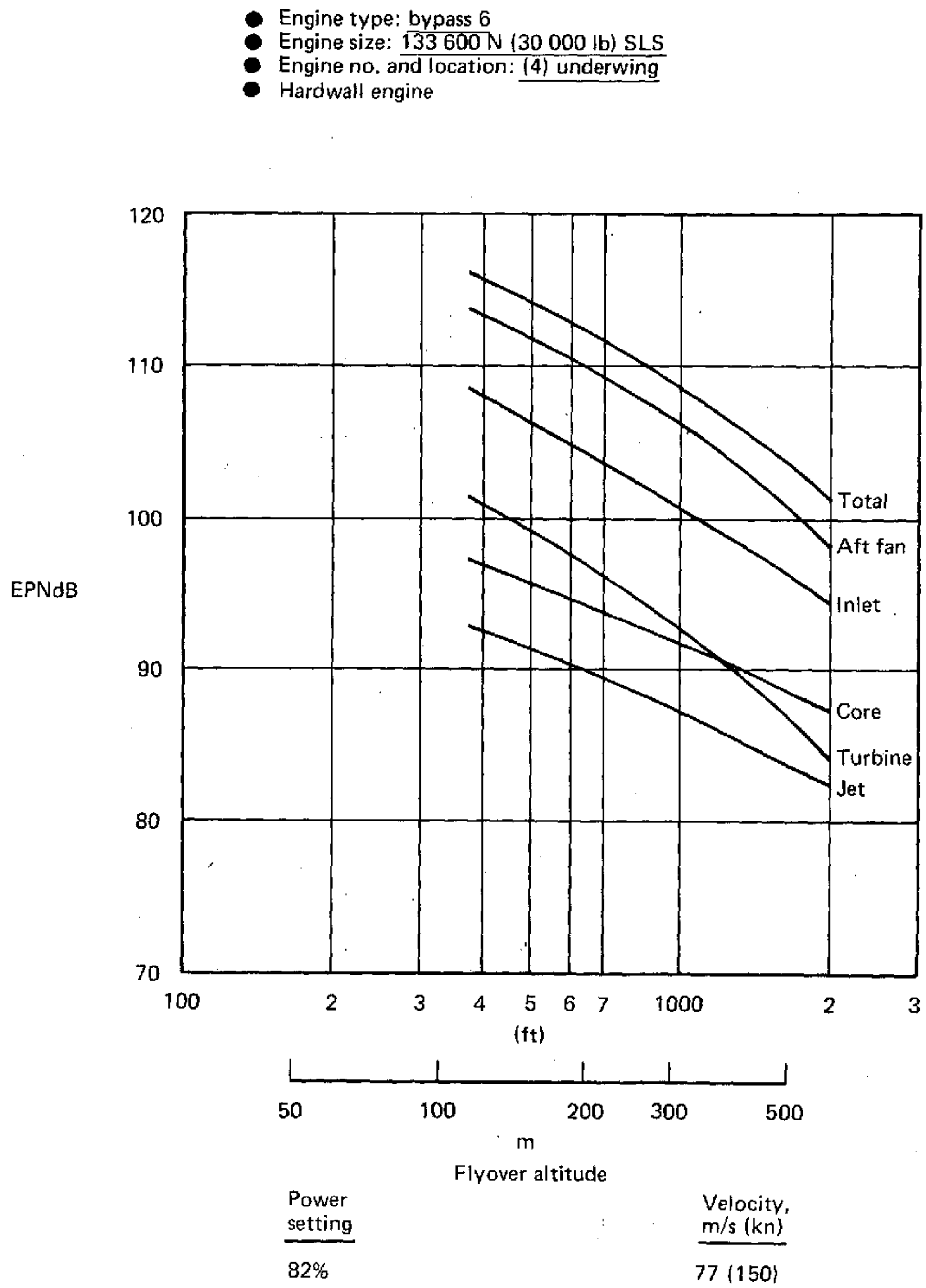


Figure 91.—Component Noise at Cutback Thrust (Hardwall Bypass 6 Engine)

- Engine type: bypass 6
- Engine size: 133 600 N (30 000 lb) SLS
- Engine no. and location: (4) underwing
- Hardwall engine

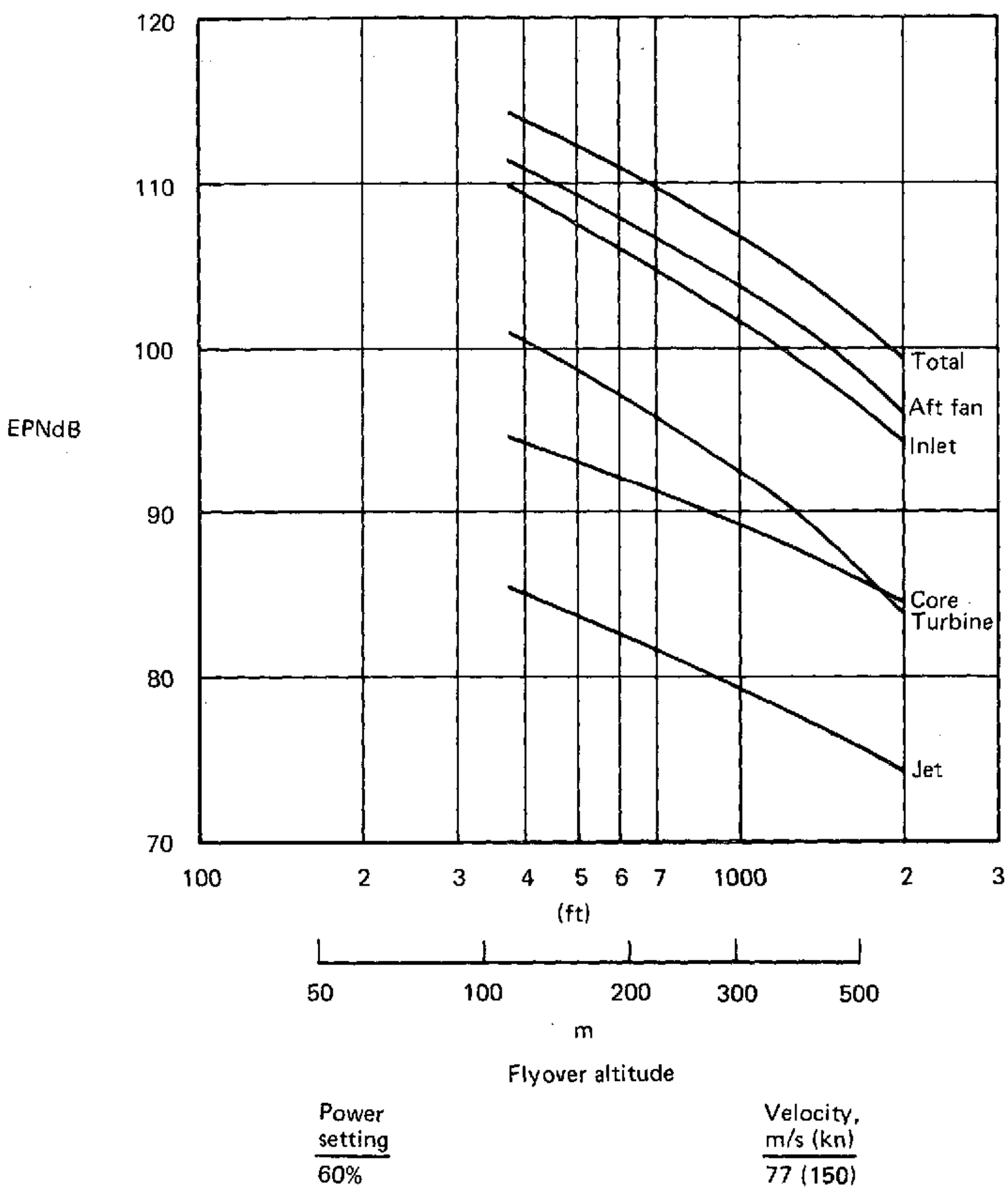


Figure 92.—Component Noise at 60% Thrust (Hardwall Bypass 6 Engine)

The preceding discussions indicate that the TAC/Energy airplane with peripheral lining only can be configured to achieve FAR 36 -3 EPNdB on approach, at flaps 50°; FAR 36 -19 EPNdB on the sideline, and FAR 36 -9.5 EPNdB during cutback for a traded FAR 36 noise level of FAR 36 -5 EPNdB. A reduction of the flap angle to 30° on approach would increase the approach speed 2 m/s (4 kn) but would reduce the approach noise to FAR 36 -6 EPNdB, resulting in a traded airplane noise level of FAR 36 -8 EPNdB.

Future development of lightweight, high-performance long inlets ($L/D \approx 1.0$) could provide 1- and 2-1/2-EPNdB quieter operations at cutback and approach conditions, respectively.

6.1.1.4 Structures Technology

The high aspect ratio wing of the TAC/Energy configuration has a significant impact on the structure. This feature leads to a longer structural beam and a higher aerodynamic lift curve slope than is typical for the current subsonic jet transports. The long beam results in high panel end loads. The high-lift curve slope causes a greater portion of the wing to be designed by gust and flutter considerations rather than by maneuver. Associated weight characteristics for this design point to the advantageous use of advanced composite materials for use in the wing structural box. Advanced composite materials are most efficient where there are large axial loads and where the relationship between bending and torsional stiffness is important. Estimates of advanced material characteristics were derived from the Advanced Transport Technology (ATT) study results (ref. 1). The availability of this technology is contingent upon the completion of the research programs recommended as part of the ATT program (ref. 8).

Two levels of advanced technology structure were considered during the ATT study. Figure 93 shows the structural material for an airplane with the technology level used in the original TAC study (ref. 2). The ply arrangement inboard of the inboard nacelle would be selected to efficiently carry the high end loads caused by the gust loading. Between the nacelles, the ply arrangement would be selected to separate the wing bending and torsional frequencies in order to meet the flutter requirements. Aluminum reinforced with multidirectional boron or graphite epoxy composite is used on the wing primary structure. Honeycomb with face sheets of DuPont PRD-49 fiber is used in the wing leading- and trailing-edge structure, fairings, and other secondary panels. Graphite epoxy honeycomb is used for all control surfaces. Bonded aluminum honeycomb is used for most of the body shell and for the skin on the horizontal and vertical stabilizers. The weight saving for these materials relative to conventional aluminum skin stringer construction is estimated to provide an approximate 10% reduction in overall airplane structural weight when compared to aluminum structure.

Figure 94 shows the structural material for an airplane that would use more graphite advanced composite primary structure. Graphite epoxy honeycomb is used for the wing, fuselage, and empennage primary structure and for all control surfaces. Honeycomb with face sheets of DuPont PRD-49 is used for the wing leading- and trailing-edge structure, fairings, and other secondary panels. Graphite epoxy is used for the non-temperature-critical area of the nacelles with the acoustic treatment integrated into the structure. The weight savings for these materials are given relative to conventional aluminum skin stringer construction. In the wing primary structure, the high panel end loads and areas that are

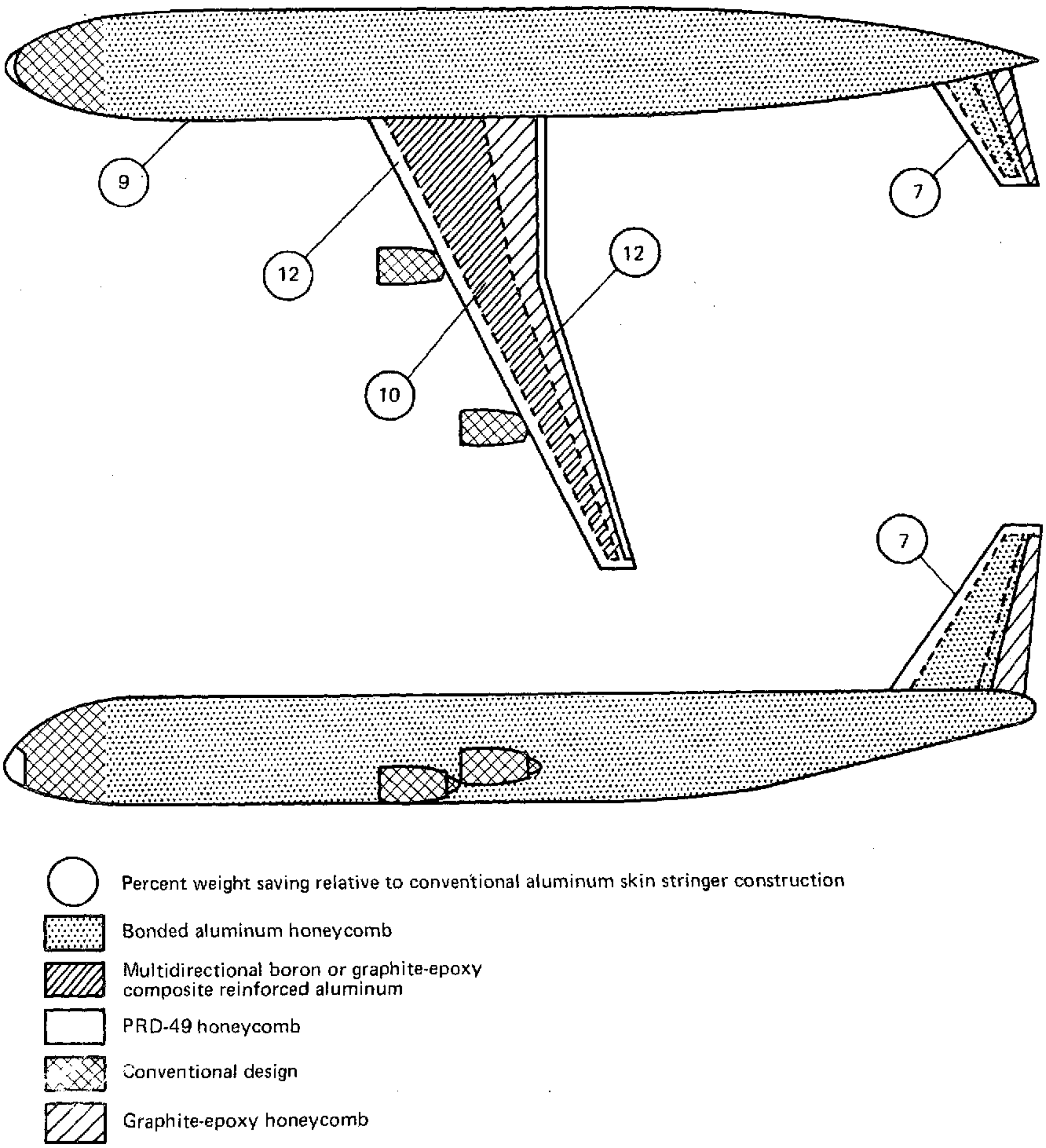


Figure 93.—Airplane With Composite—Reinforced Aluminum and Bonded Aluminum Honeycomb Primary Structure

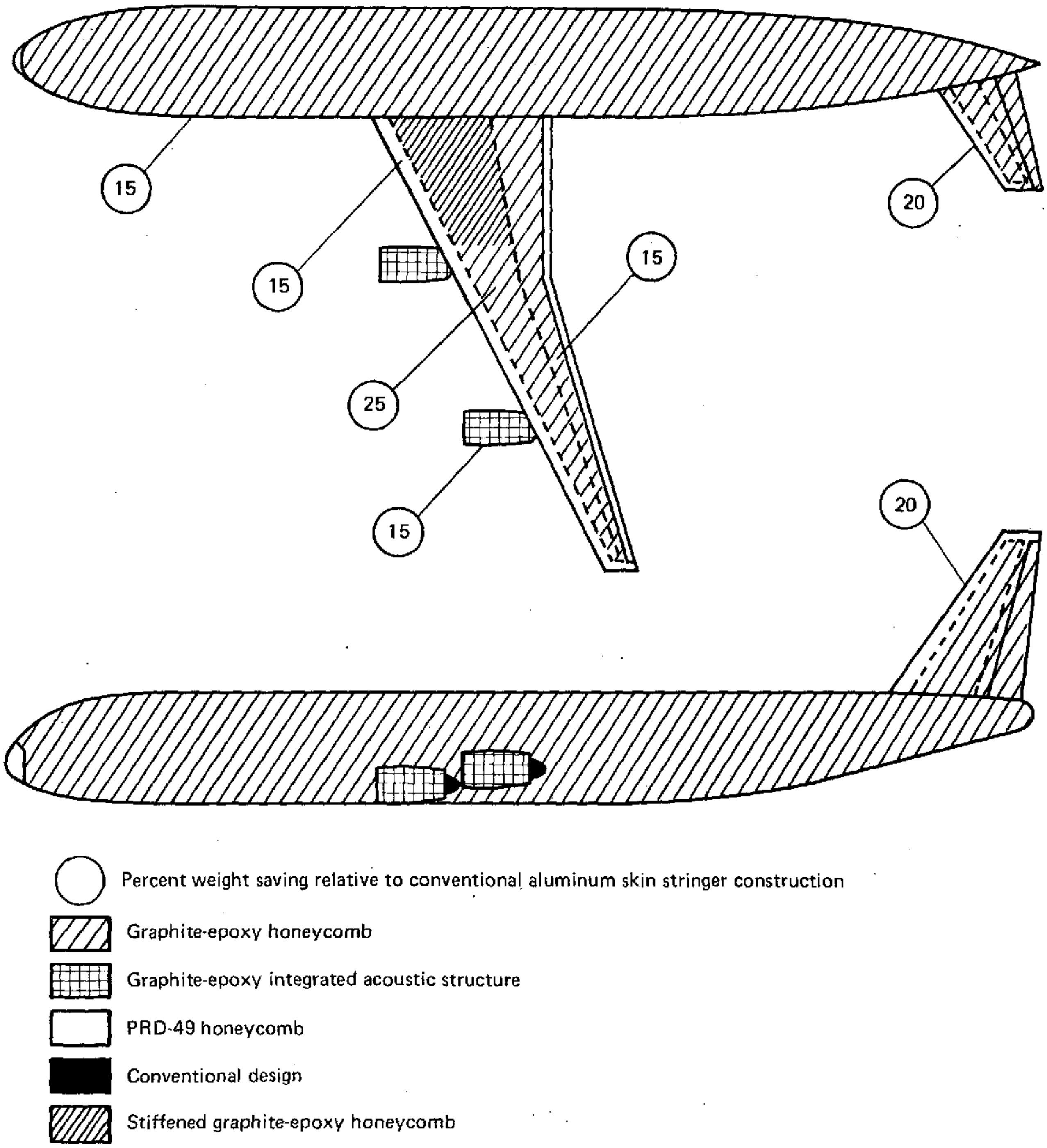


Figure 94.—Airplane With All Composite Primary Structure

stiffness critical due to flutter requirements make the graphite epoxy construction very attractive and result in an estimated structural weight saving of 25%.

Review of the status of development of composite materials for commercial transport application indicated that the level of composites used for the original TAC study (fig. 93) should be used for the TAC/Energy airplane. This level of advanced structure represents the maximum usage of advanced composite consistent with the specified operational time period for the airplane.

6.1.1.5 Flight Control Technology

The TAC/Energy airplane was evaluated for adequate longitudinal, lateral, and directional control surface size. Estimated values were used for the aerodynamic, aeroelastic, and propulsion coefficients, together with predicted weight and inertia estimates.

The vertical tail size was determined by the low-speed engine-out control capability during takeoff (V_{MCA}). The geometry between the aft center-of-gravity limits and the main landing gear and nose gear location satisfies the nose gear steering requirements established for transport airplanes.

The horizontal tail size was determined from the following: (1) forward c.g. boundary nosewheel lift-off, (2) aft c.g. boundary-maneuver point at cruise flight, and (3) a c.g. range of 32% MAC required for loading the airplane.

The lateral controls consist of a combination of ailerons and spoilers. The required surface size was estimated using theoretical methods to calculate control surface effectiveness and compared to calculated aerodynamic and structural data for existing transport airplanes. The roll control power required to reach 30° of bank in 2.5 sec on approach was met, using full aileron and spoiler deflection. The roll control power to reach 30° of bank in 20 sec for M = 0.8 cruise includes an estimate for degradation in rolling moment caused by aeroelastic effects.

It was assumed that acceptable lateral-directional flying qualities would be provided by a full-time stability augmentation system with the appropriate level of redundancy.

6.1.1.6 Systems Technology

The systems of the airplane are the same as those of the TAC (ref. 2) airplane except for the following described changes. (Four independent hydraulic and four independent electrical power systems are retained). The two large APU's have been replaced by a single small APU, which provides airplane ground electric and pneumatic power and also supplies power to the hydraulic system to drive the powered wheels. Engine bleed is used for engine inlet and wing thermal anti-icing and cabin air source. The quantity of engine bleed airflow supplied to the cabin has been reduced by 50%. This reduction is compensated for through the use of revitalized (filtered and cleaned) recirculated cabin air. Two small air cycle cooling units condition the engine bleed air. A vapor cycle cooling unit conditions the recirculated cabin air.

6.1.1.7 Weight Technology

The weights for the TAC/Energy airplane were developed by first applying the benefits of advanced technology structure and then incorporating the terminal compatibility features described in section 5.2. The same level of advanced structure technology used in the original TAC study (ref. 2) was used on the TAC/Energy airplane. Wing structural weight benefits were considered in relatively greater depth because of the level of structural definition resulting from the aeroelastic analysis of the wing planform study. The percentages of weight benefits for advanced technology structure were distributed as follows:

Wing	11.9%
Horizontal tail	6.5%
Vertical tail	6.5%
Body	9.1%
Landing gear	8.4%

Weight penalties for incorporation of the terminal compatible features are shown in table 17 and are significantly less than incurred on the TAC configuration. The TAC/Energy concept does not have the large drag brakes which were used for the two-segment approach in the TAC study. The other major weight difference is due to eliminating the requirement for large flight-operable APU's as the power source for secondary power systems. A more detailed breakdown of the principal weight categories for the TAC/Energy concept is provided in section 6.2.

Table 17.—Terminal Compatible Features for Energy Airplane

	Uncycled Δ weight
(Δ 1) Programmed flaps for wing tip vortex dissipation	9 kg (+ 20 lb)
(Δ 2) Powered wheel—main landing gear	667 kg (+1 470 lb)
Increase APU horsepower	250 kg (+ 550 lb)
Increase hydraulic system capacities	181 kg (+ 400 lb)
Integrate powered wheels in MLG	236 kg (+ 520 lb)
(Δ 3) Avionics	91 kg (+ 200 lb)
(Δ 4) Rapid deceleration	417 kg (+ 920 lb)
Increase unsprung/sprung ratio on MLG	340 kg (+ 750 lb)
Increase brakes	77 kg (+ 170 lb)
(Δ 5) High-speed runway turnoff	82 kg (+ 180 lb)
Nose gear side load	
Σ TAC features on energy airplane	1 266 kg (+2 790 lb)

6.1.2 COMPARISON CONCEPT CHARACTERISTICS

The resulting fuel usage, range factor, approach velocity, propulsive efficiency (V/SFC), thrust/weight ratio, and L/D versus span/ $\sqrt{\text{wetted area}}$ for the three comparison concepts are shown in figures 95 through 100. The values shown are based on the assumption that the full calculated potential for the ATT-E, TAC-E, and TAC/Energy concepts can be realized from adequate R&T programs. The contractor estimates that the calculated potential fuel reduction could be eroded to a value as low as 23% when applied to a real-world detail design. For the CWB concept, those figures reflect three values: (1) the original values as used during the TAC study evaluation–noted as CWB on the figures, (2) values of the original CWB flown at M = 0.82 rather than 0.85, and (3) values as updated for this study using long-range cruise and resizing the wing area and engine thrust to meet the design range–noted as CWB-E. A breakdown of the principal weight categories for the three updated comparison concepts is provided in section 6.2.

A three-step process was followed during update of the ATT and TAC concepts. Each concept, as originally evaluated, was corrected to reflect long-range cruise procedures, revising the propulsion weight to a current advanced technology base, and the more favorable aerodynamic data that were available during this study. Figures 95 through 100, therefore, show three values for both the ATT and the TAC concepts: (1) the original value noted as ATT and TAC, (2) the value calculated using long-range cruise (ATT_{LRC} and TAC_{LRC}), and (3) the value calculated using both long-range cruise and favorable aerodynamic data base–noted as ATT-E and TAC-E. Key points regarding the values shown are described in the following paragraph.

Using long-range cruise procedures on the CWB airplane and resizing the wing area and engine thrust resulted in a 7.5% reduction in fuel usage. Had the airplane not been resized, the fuel saving would have been 3% to 4.5% less. The ATT and TAC airplanes flown at a similar reduction in cruise speed did not benefit substantially because of their drag rise characteristics. However, changing to the contractor airfoil data base, with its more conventional drag rise, results in a fuel saving of 14.5% for the ATT-E airplane as compared to the CWB-E, even accounting for the increased wing (decreased thickness) and propulsion (technology) weights. The TAC-E airplane would have similar benefits to fuel savings and airplane size except for the additional constraint imposed by takeoff noise. Even so, the net fuel saving was 9% for the TAC-E airplane.

6.2 IMPACT ASSESSMENT AND COMPARISON

6.2.1 INTRODUCTION

The objective of the activity described in this section was to assess the costs and benefits (from the technical and economic standpoints) associated with configuring the TAC/Energy airplane concept with emphasis on fuel conservation as well as terminal area compatibility. Results of the assessment are provided in the following paragraphs. In several cases, the results are displayed in a form that provides a comparison with a state-of-the-art airplane concept in order to relate results to existing levels of technology. The assessment included an evaluation of the economic worth of delay reduction estimated to be achievable, assuming proper research and technology and the implementation of desirable features on a major part of the future commercial fleet.

Range = 5 556 km (3 000 nmi)
Payload = 18 140 kg (40 000 lb)

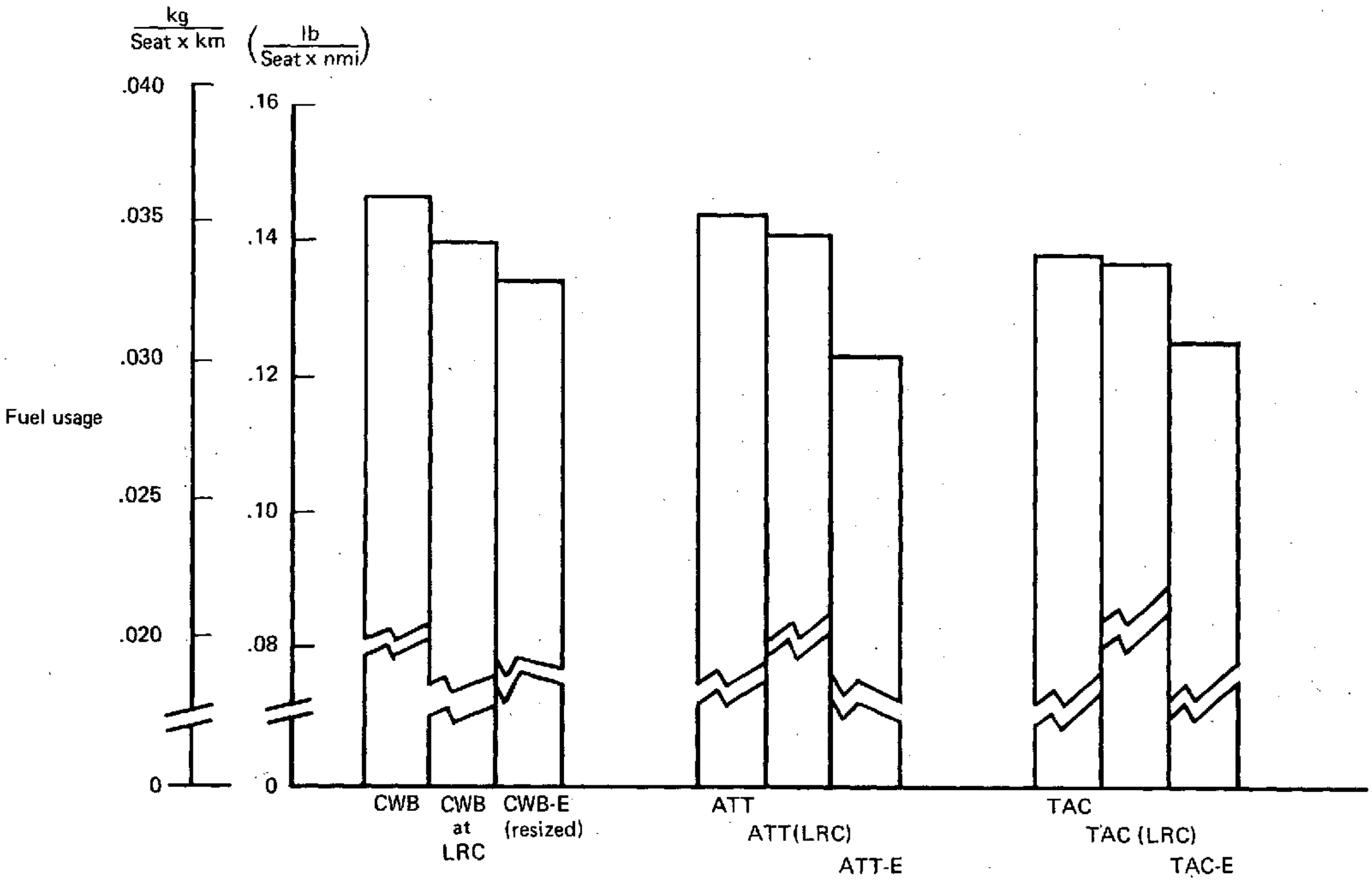


Figure 95.—Summary Fuel Usage of Comparison Airplanes

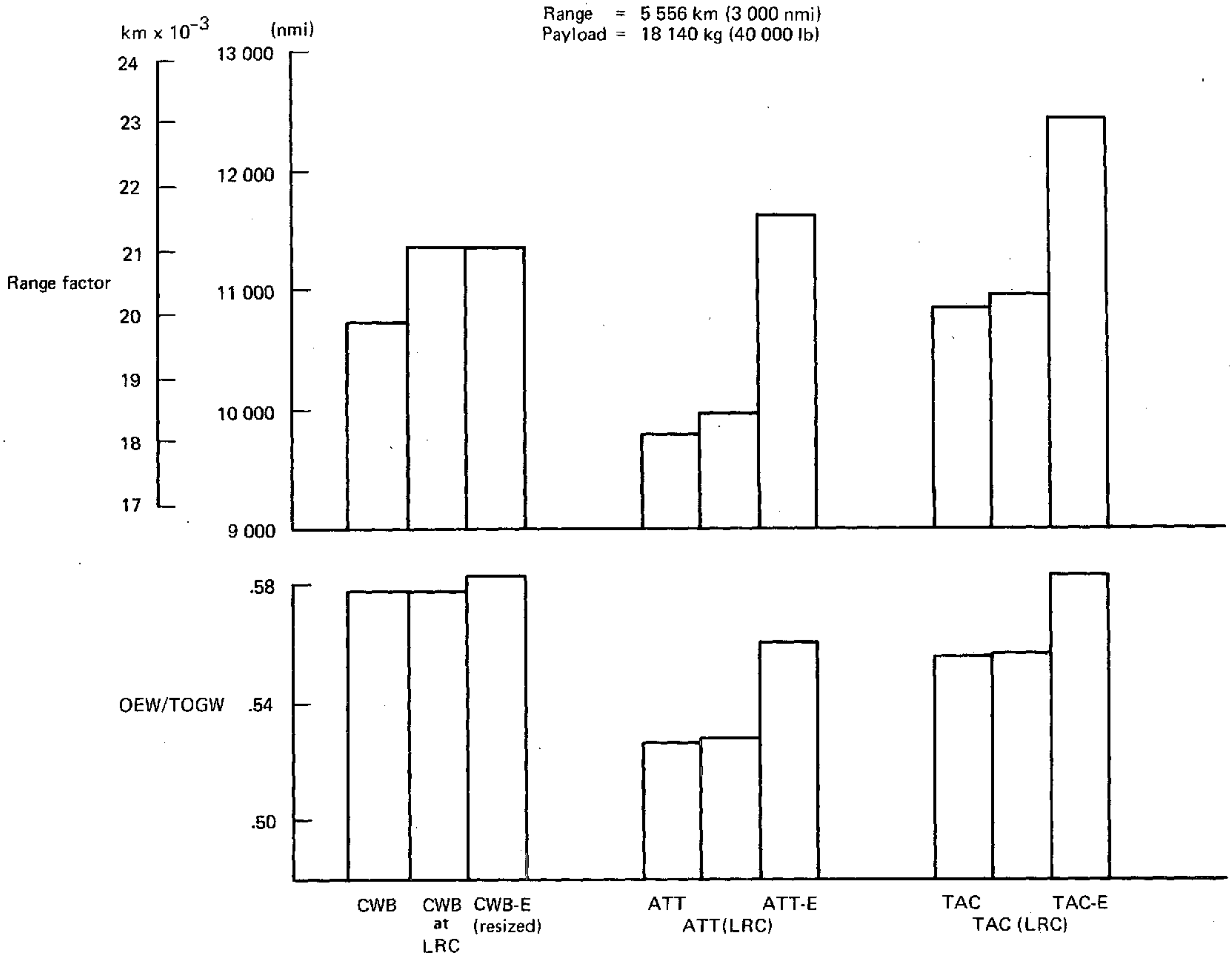


Figure 96.—Summary Performance Characteristics of Comparison Airplanes

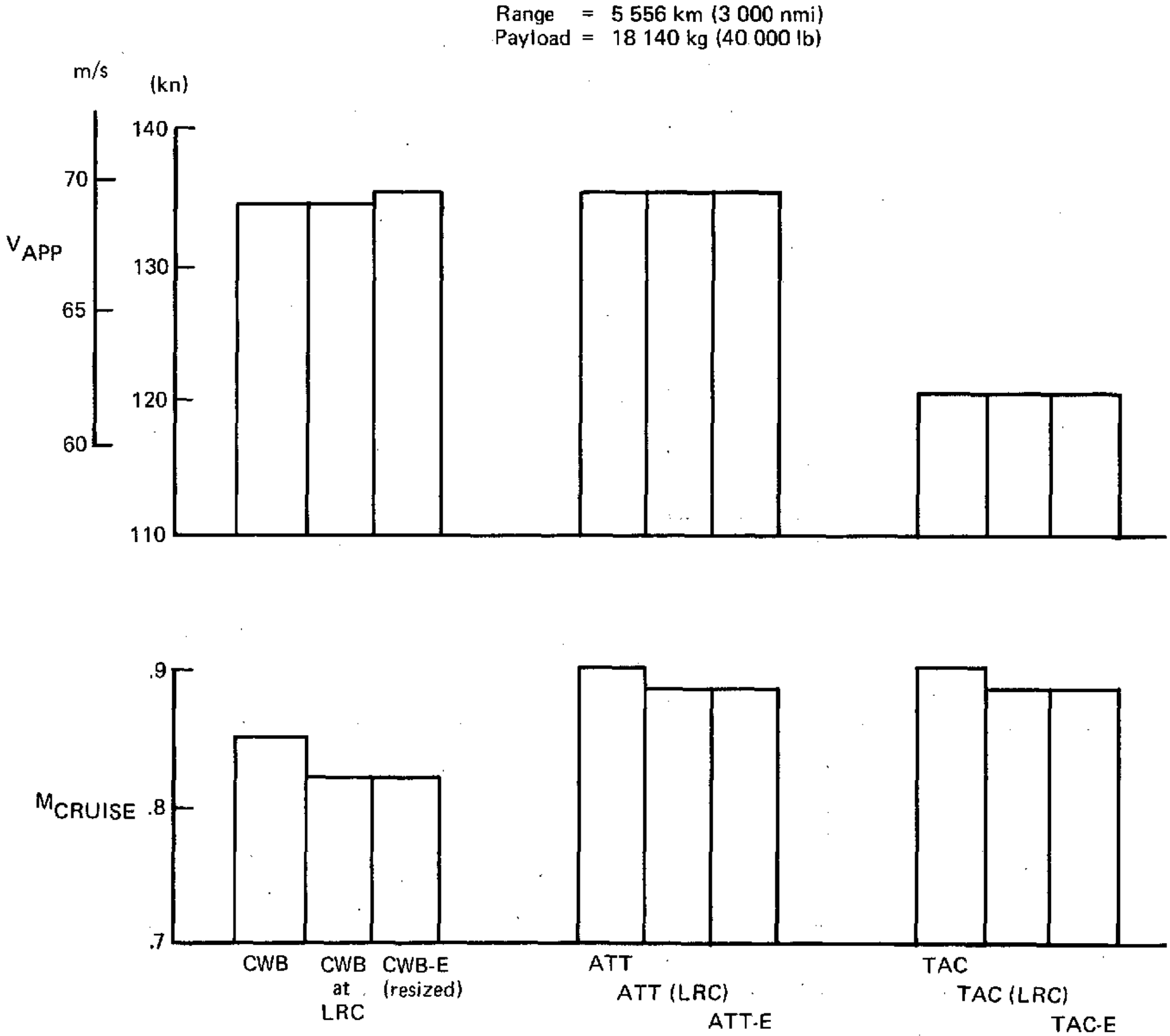


Figure 97.—Additional Performance Characteristics of Comparison Airplanes

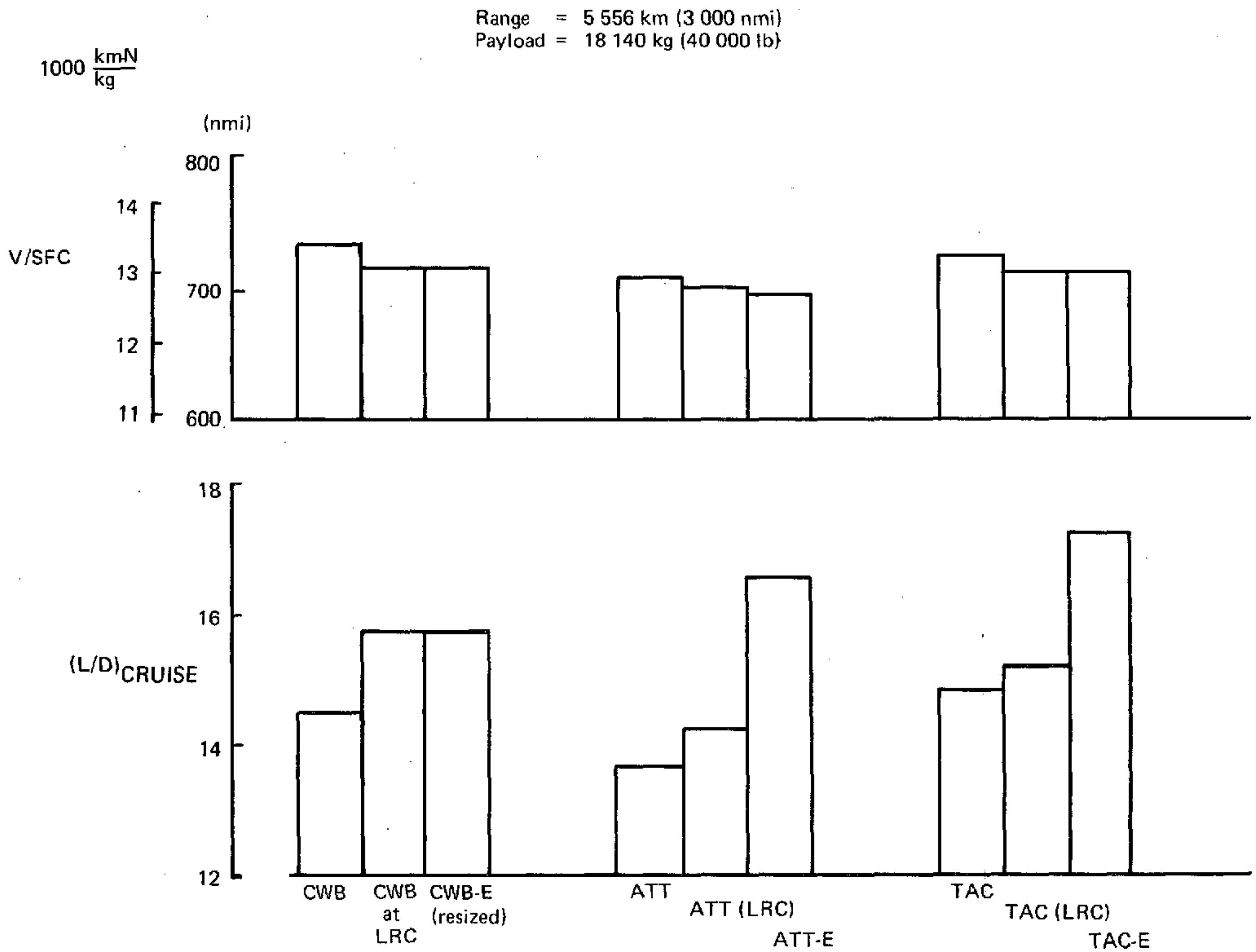


Figure 98.—Additional Performance Characteristics of Comparison Airplanes

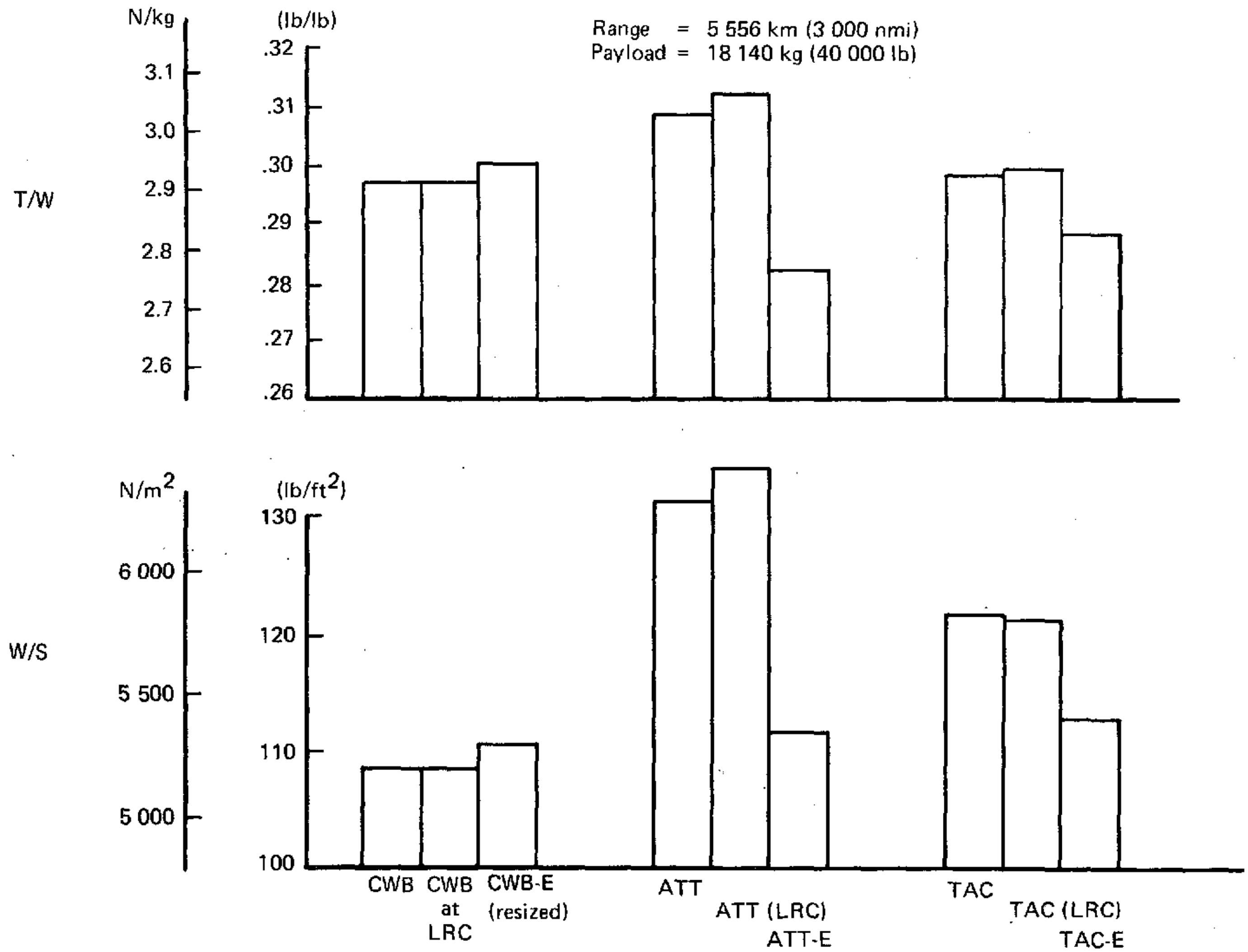


Figure 99.—Engine and Wing Size Comparison—Airplane Characteristics Summary

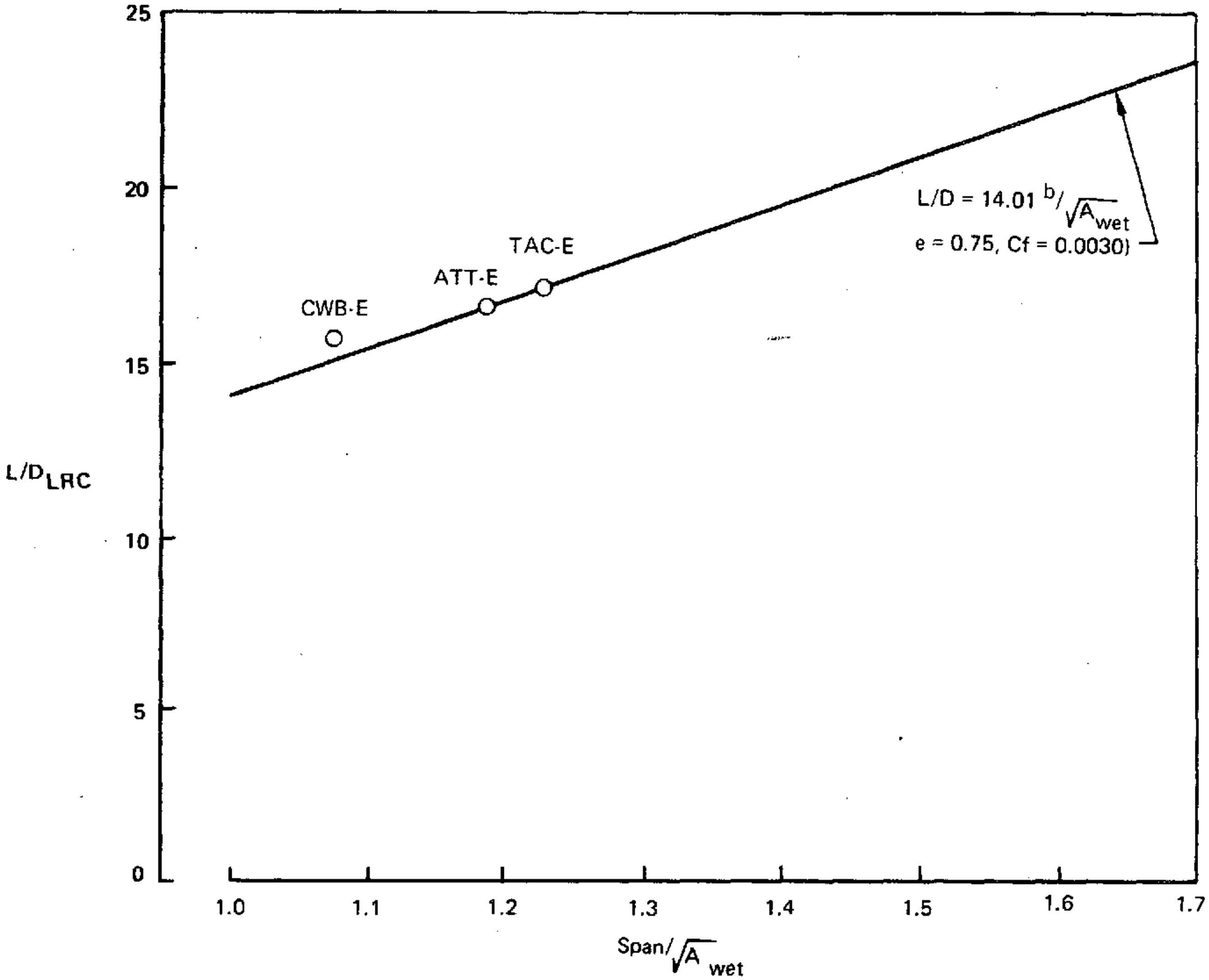


Figure 100.—Effect of Wetted Area and Span on Cruise Efficiency

Section 6.2.2 presents a detailed technical comparison of the four airplane concepts that were central to the study, in terms of principal airplane design parameters. Section 6.2.3 presents an economic comparison of the four concepts in a manner that accounts for assumed differences in delay that would be experienced during operational use. From the technical standpoint, comparisons are provided for fuel usage, takeoff gross weight, and auxiliary airplane performance parameters such as field length capability, altitude capability, range factors, and others. The following paragraphs, therefore, provide a comparison of both the technical and economic characteristics of the concepts, in terms of the principal terminal-compatibility characteristics: namely, congestion, noise, and emissions, as well as fuel usage.

6.2.2 TECHNICAL ASSESSMENT AND COMPARISON OF STUDY AIRPLANES

Table 18 contains a comparison of the principal size, geometry, performance, and noise characteristics of the study concepts. As shown, all aircraft were designed for the same 196-passenger, 5556-km (3000-nmi) range. The principal design parameters that affect the concept size are range and payload specification, takeoff field length and approach speed constraints, and initial cruise altitude capability.

The CWB-E wing and engine sizes were established by takeoff field length and minimum fuel usage. Similarly, the ATT-E was thrust sized by takeoff field length and minimum fuel usage.

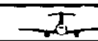
The TAC-E wing and engine sizes were selected primarily from takeoff noise considerations. The engine size of the TAC-E was sized to achieve sufficient climb gradient to reduce takeoff noise to approximately -15 EPNdB relative to FAR Part 36.

In contrast, the TAC/Energy wing and engine sizes were established by approach speed and minimum fuel usage. Approach speed is not an independent consideration from approach noise measured at the FAR Part 36 noise station. This situation arises because additional wing area can be traded against decreased flap setting in order to achieve a desired noise level and still satisfy the approach speed constraint. The TAC/Energy concept wing was sized using maximum flap deflection of 50°. It could have been sized at a lower flap deflection (30°) with a slightly larger wing. This would reduce approach noise by approximately 3 EPNdB at a fuel and DOC penalty of 0.5% and 1.5%, respectively. However, the configuration would have a maximum glide slope capability of -3.5°.

The engines were sized for minimum fuel usage and not on the ability to achieve sufficient climb gradient to reduce takeoff noise to -15 EPNdB below FAR Part 36. Had the airplane concept been constrained for takeoff noise, a 3.5% penalty to fuel usage would have resulted. This noise level could have been achieved by an engine size increase or use of acoustical engine treatment. A typical engine and wing sizing chart is shown in figure 101 for the TAC/Energy concept showing the effect of performance constraints.

The airplane concept as sized assumes that the wake turbulence problem can be solved by some "zero penalty fix" or at worst by a very small penalty to fuel usage. At this time, the current definition of "programmed" flaps (retracting the outboard half of the flaps) to achieve a lift distribution with acceptable levels of wake turbulence probably allows

Table 18.—Summary Aircraft Characteristics

Characteristics	 CWB–E	 ATT–E	 TAC–E	 TAC/Energy
Cruise speed, Mach	0.82	0.885	0.885	0.80
Takeoff gross weight, kg (lb)	147 200 (324 600)	132 400 (291 800)	140 800 (310 500)	115 300 (254 200)
Operating weight empty, kg (lb)	85 890 (189 360)	74 080 (163 320)	82 120 (181 030)	67 351 (148 480)
W/S, N/m^2 (lb/ft^2)	5 290 (110.5)	5 330 (111.4)	5 390 (112.6)	5 690 (118.9)
T/W, N/kg	2.94 (0.30)	2.76 (0.282)	2.83 (0.288)	2.34 (0.239)
Thrust/engine, sea level static, N (lb)	144 100 (32 400)	121 900 (27 400)	99 600 (22 400)	67 600 (15 200)
Number of engines/type	3/CF6-6D	3/ATSA 4-2800-24	4/ATSA 4-2800-24	4/BPR 6.0
Acoustics	Peripheral lining	2 rings/1 splitter	2 rings/1 splitter	Peripheral lining
Wing area, m^2 (ft^2)	272.9 (2937)	243.2 (2 618)	256.1 (2 757)	198.6 (2 138)
Sweep, deg	35.0	36.5	36.5	25.0
Aspect ratio	6.8	7.6	9.0	12.0
Performance				
Takeoff field length at 302 m, 32.2° C (1000 ft, 90° F), m (ft)	2 530 (8 300)	2 530 (8 300)	2 530 (8 300)	2 530 (8 300)
Approach speed, m/s (kn)	69.4 (135)	69.4 (135)	61.7 (120)	61.7 (120)
Initial cruise altitude capability, m (ft)	11 130 (36 500)	11 550 (37 900)	12 130 (39 800)	11 050 (36 300)
Range factor, km (nmi)	21 020 (11 350)	21 520 (11 620)	23 020 (12 430)	24 800 (13 390)
*Fuel usage, $\frac{kg}{seats \times km}$ ($\frac{lb}{seats \times nmi}$)	0.0328 (0.134)	0.0301 (0.123)	0.0306 (0.125)	0.0225 (0.092)
Community noise (Est/est–FAR Part 36) using FAR abatement procedures:				
Takeoff noise with cutback power	96.6/-7.0	95.4/-7.4	88.1/-15.0	92.1/-9.6
Sideline noise	95.5/-10.7	93.3/-12.6	90.3/-15.8	86.2/-19.3
Approach noise	97.7/-8.5	96.9/-9.1	96.7/-9.4	102.1/-3.4
Traded noise	-8.7	-9.4	-11.4	-5.4

5556 km (3000 nmi) range; 18 140 kg (40 000 lb) payload *5556 km (3000 nmi) stage length

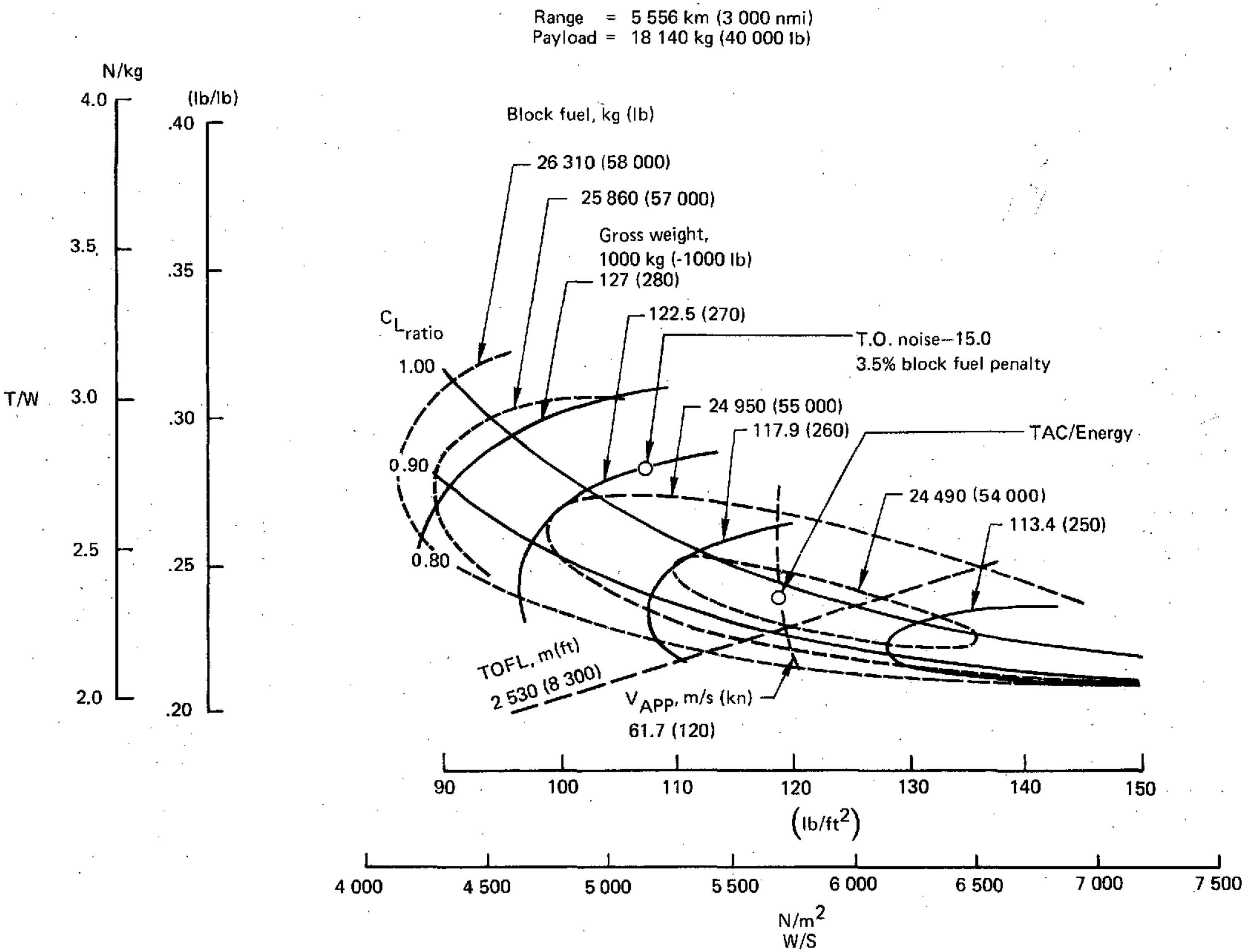


Figure 101.–TAC/Energy Sizing Thumbprint

separation distances on the order of 1.85 to 5.56 km (1 to 3 nmi) for those airplanes currently required to fly 5.56 to 9.26 km (3 to 5 nmi) apart. However, the loss of low-speed performance from the current definition "programmed" flaps required decreasing wing loading by 25% to meet the approach speed constraint and increasing thrust loading by 19% to optimize fuel burn. This would cause a large fuel burn (7%) and economics (9%) penalty for the "programmed" flaps as currently defined.

6.2.2.1 Fuel Usage

Figures 102, 103, and 104 present a summary comparison of the fuel usage and the principal performance parameters, range factor, and OEW fraction. Relative to the CWB-E concept, the ATT-E fuel usage is approximately 8% less as a result of improved cruise L/D (advanced airfoils), improved OEW fraction (advanced technology structures), and decreased propulsive efficiency (S-duct and acoustical lining). The range factor, on the other hand, shows only slight improvement. This is due to a combination of increased cruise speed and L/D (AR and advanced airfoil technology) offset by propulsion installation inefficiency incurred because of the extensive use of acoustical treatment. Similarly, the TAC-E fuel economy would have been approximately 10% better, except a 4% fuel burn penalty was traded for a -15-EPNdB takeoff noise relative to FAR Part 36. The TAC-E concept incurs penalty in OEW due to the many features added to provide terminal compatibility. Of these features, the changes to improve low-speed aerodynamics also provided improvement to cruise range factor, primarily from the increased aspect ratio and increased wing area, both of which tend to improve cruise L/D.

Assuming the full fuel reduction potential can be realized, the TAC/Energy concept yields a fuel usage approximately 30% better than the resized CWB-E (32% better than the CWB), including the weight penalty of the TAC features, which was approximately 2%. The preceding 30% does not include effects due to delay reduction. The TAC/Energy concept differs dramatically in fuel usage from the TAC-E, approximately 26%, with 3% of this saving associated with the revised list of terminal compatibility features. The substantial number of other changes (cruise speed, wing geometry, engine cycle, and propulsion efficiency) accounts for the remaining fuel savings.

Figure 105 presents a slightly more detailed comparison showing approach speed, cruise Mach number, and a breakdown of range factor into its aerodynamic and propulsive efficiency factors. A comparative weight breakdown of the study concepts is shown in table 19, while comparative cruise efficiency is shown in figure 106. One additional fact indicated by figure 105 is a slight improvement in propulsive efficiency of the TAC-E compared to the ATT-E. This improvement in efficiency is a result of (1) changing the engine configuration from one that includes S-duct internal losses to the four-engine on-the-wing configurations used for the TAC airplanes, and (2) an improvement realized in the cruise SFC for the primary engines as a result of using an in-flight dedicated auxiliary power unit for the TAC-E concept. The SFC savings in the engines result from reduced penalties associated with bleed and horsepower extraction which were offset by fuel expended by the APU units (i.e., the fuel expended by the APU unit is about equivalent to that saved by the engines).

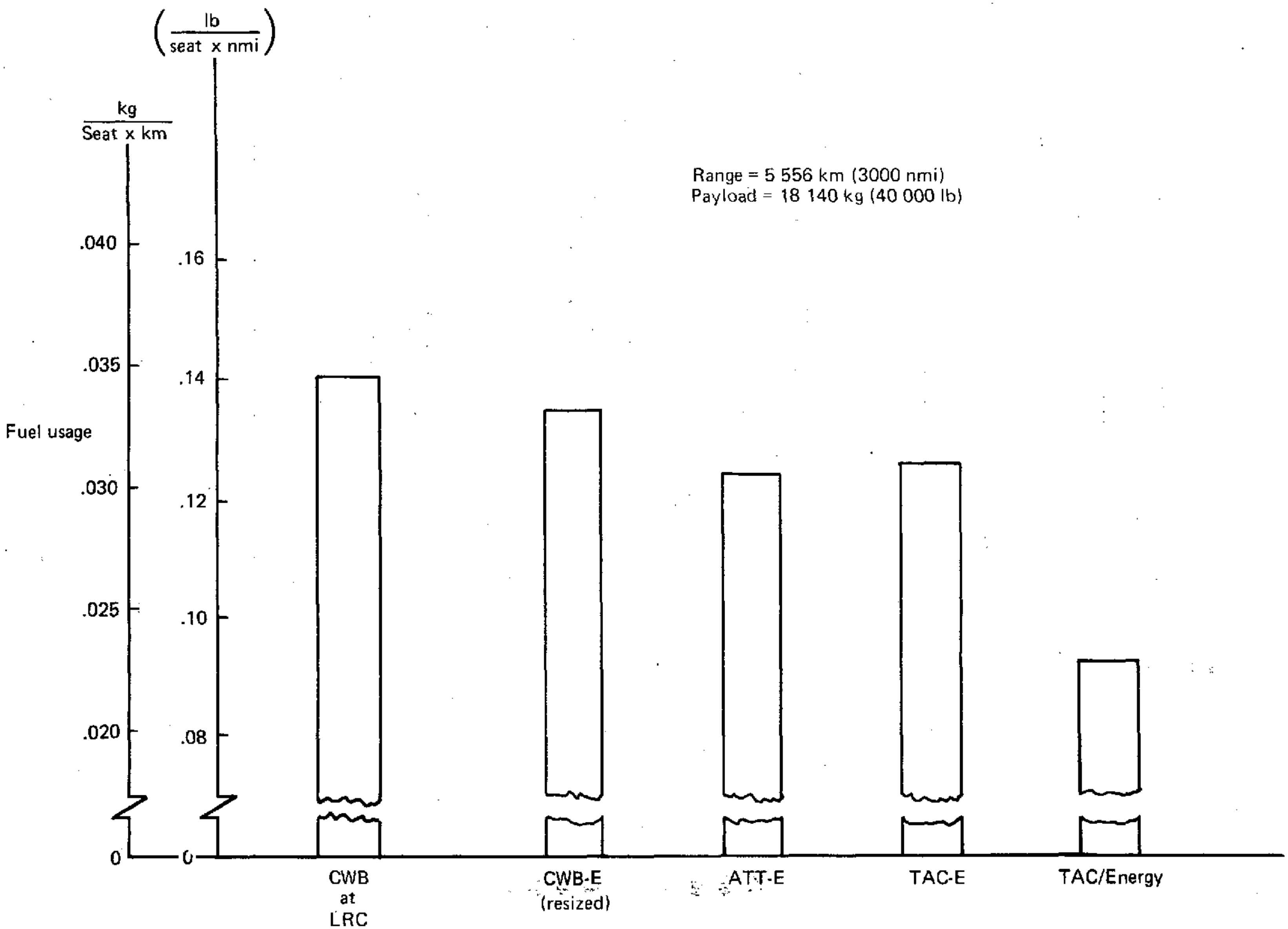


Figure 102.—Fuel Burn Characteristics of Study Airplanes

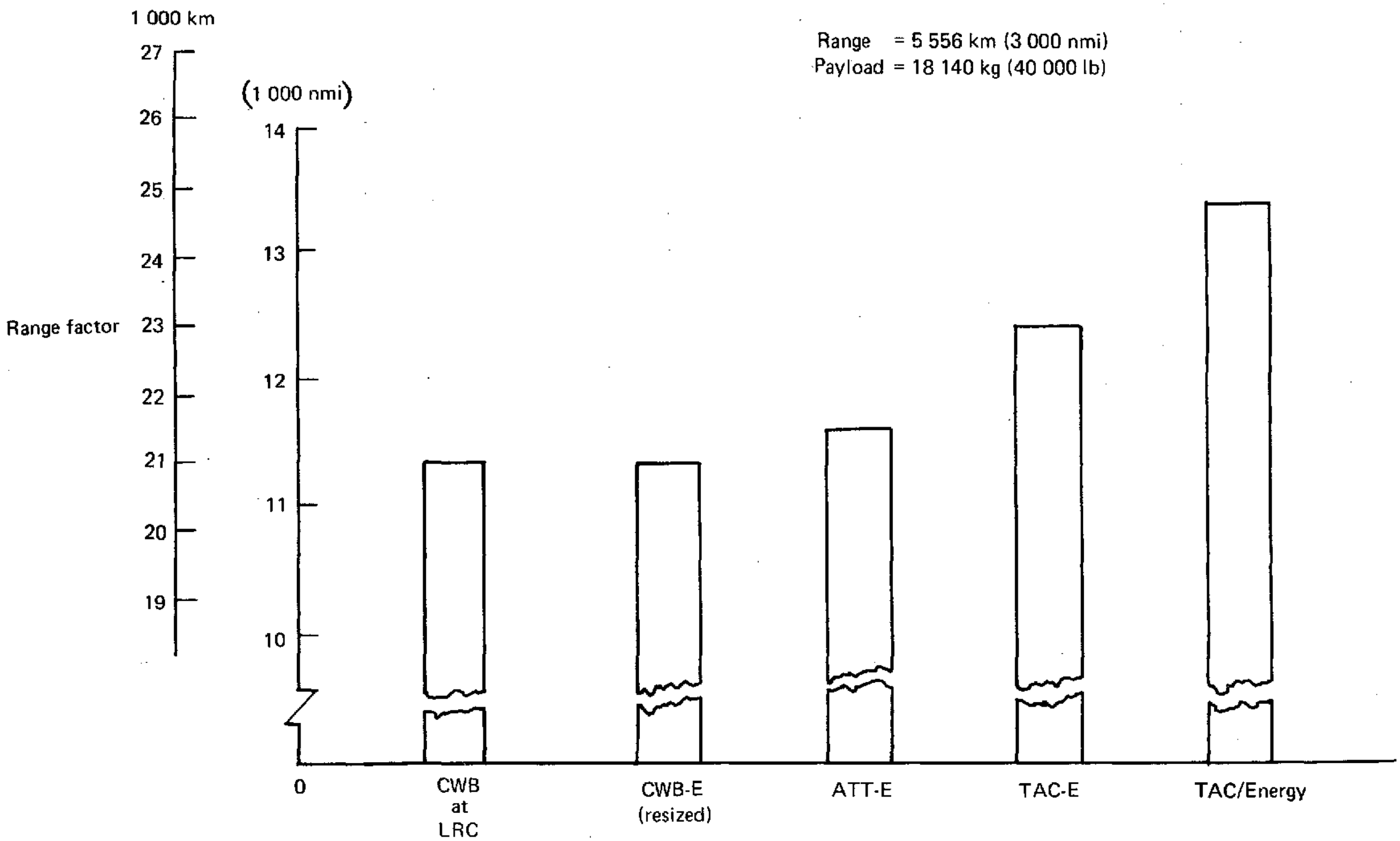


Figure 103.—Summary Performance Characteristics of Study Airplanes

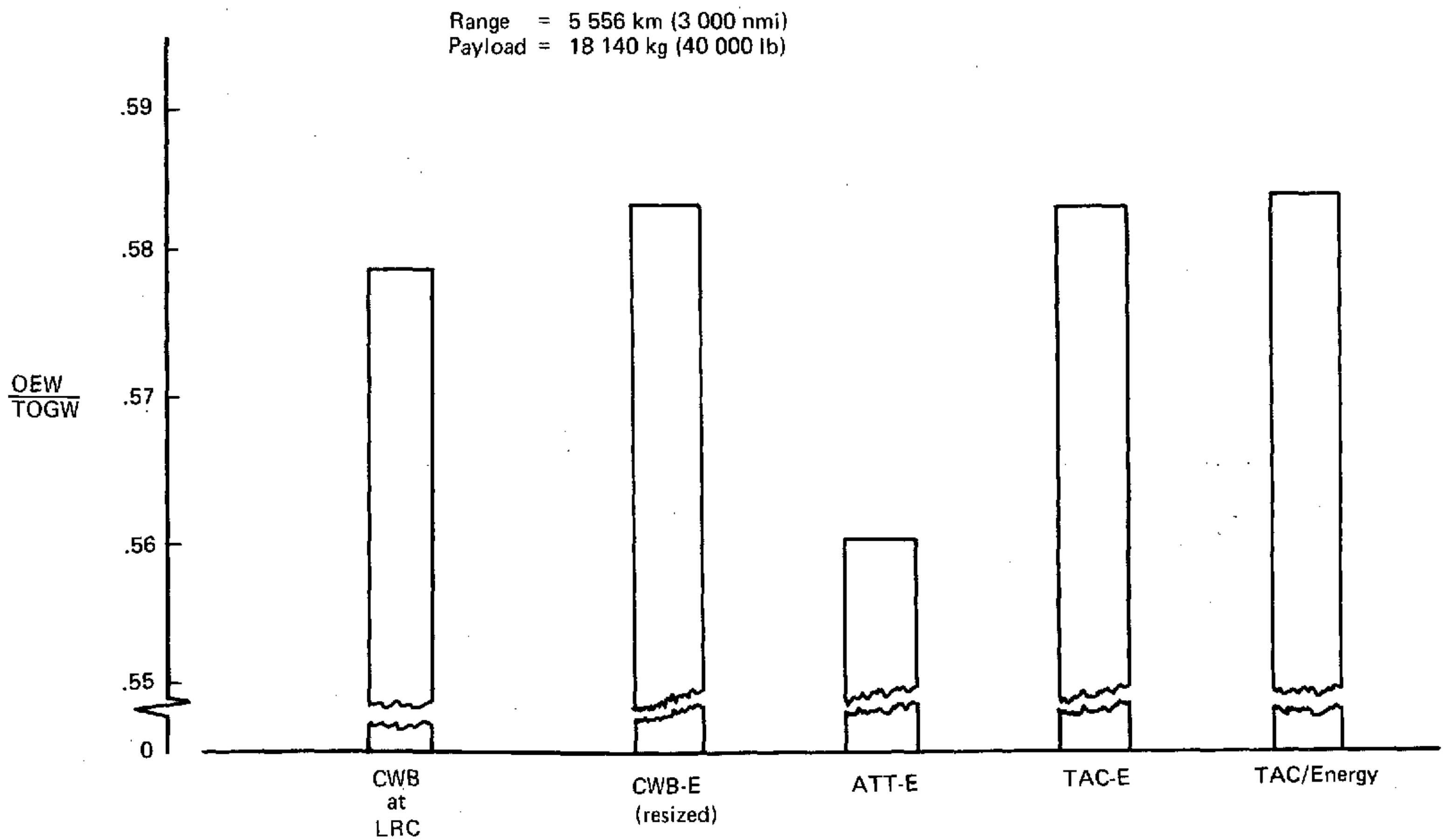


Figure 104.—Summary Performance Characteristics of Study Airplanes

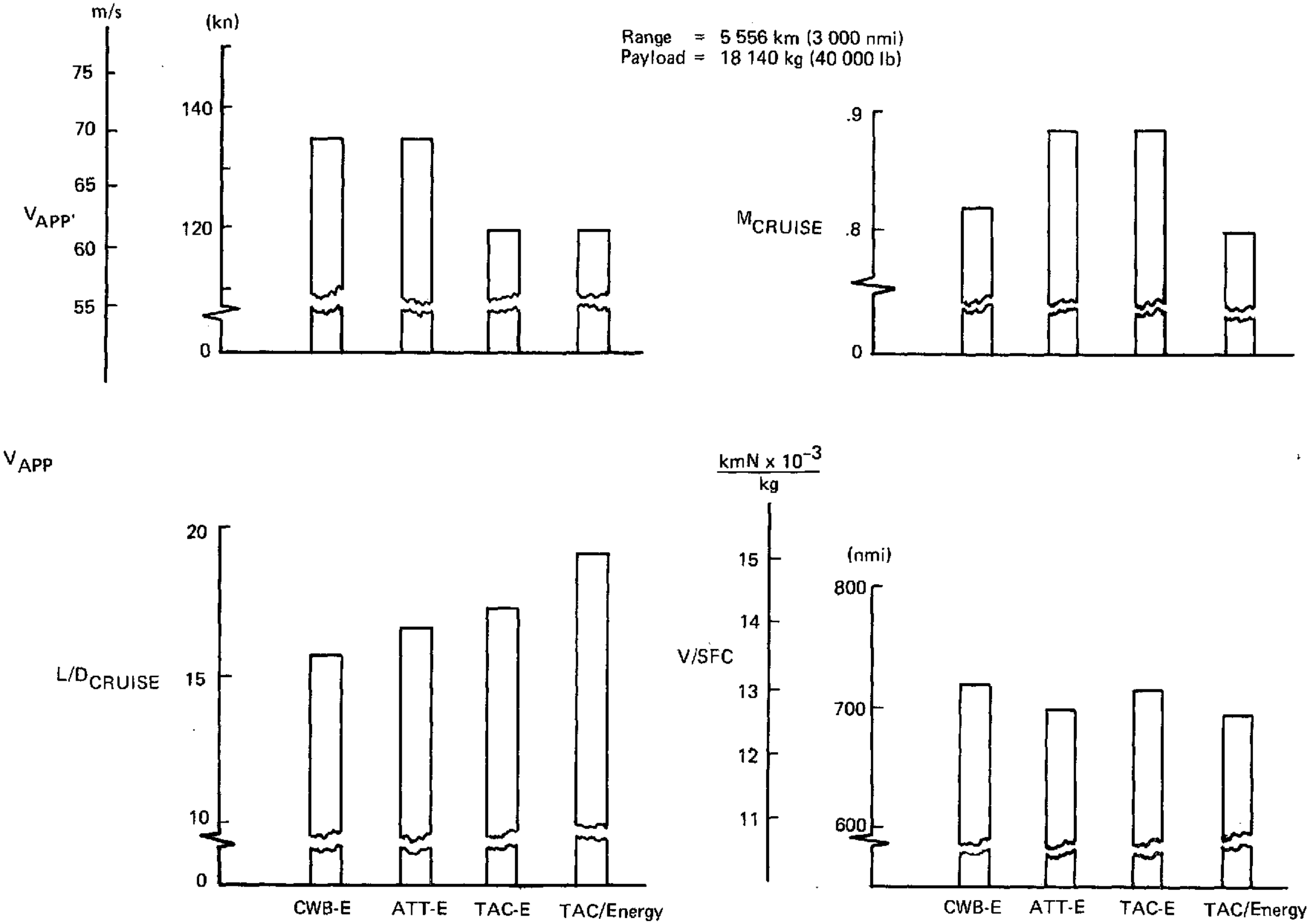


Figure 105.—Additional Performance Characteristics Comparison

Table 19.—Comparative Weights Breakdown

Item.	ATT-E, kg (lb)	CWB-E, kg (lb)	TAC-E, kg (lb)	TAC/Energy, kg (lb)
Wing group	15 654 (34 510)	15 663 (34 530)	19 069 (42 040)	13 749 (30 310)
Vertical tail	885 (1 950)	1 483 (3 270)	1 275 (2 810)	807 (1 780)
Horizontal tail	1 497 (3 300)	3 298 (7 270)	1 447 (3 190)	1 383 (3 050)
Body group/nacelle & strut	17 123 (37 750)	22 145 (48 820)	18 765 (41 370)	16 670 (36 750)
Landing gear	5 493 (12 110)	7 847 (17 300)	6 396 (14 100)	5 779 (12 740)
Propulsion group	10 301 (22 710)	10 809 (23 830)	10 496 (23 140)	6 378 (14 060)
Fixed equipment	17 210 (37 940)	18 171 (40 060)	18 720 (41 270)	16 670 (36 750)
Standard & operational items	5 094 (11 230)	5 484 (12 090)	5 157 (11 370)	4 940 (10 890)
Miscellaneous	871 (1 920)	1 021 (2 250)	871 (1 920)	975 (2 150)
OEW	74 128 (163 420)	85 921 (189 420)	82 196 (181 210)	67 351 (148 480)

The overall efficiency (V/SFC) of the TAC/Energy engine cycle (considering the lower cruise speed, redesigned ECS system, and BPR 6.0 peripherally treated engines) is equivalent to the ATT-E concept but slightly worse ($\approx$ 3.5%) than the TAC-E concept.

Figure 107 summarizes the basic thrust loading and wing loading characteristics for the four study airplanes. The reasons for the data trends have been discussed previously.

6.2.2.2 Congestion

All the features that were added to the TAC airplane for congestion relief (wing trailing vortex modification, reduced approach speed, increased ground deceleration capability, high-speed turnoff, powered wheels, and improved avionics) are included in the final low-energy version. None of the other changes to the airplane affect the congestion. Therefore, assuming wake vortex effects can be minimized by use of the programmed flap approach, the congestion relief projected for the TAC airplane will also be realized for the TAC/Energy airplane.

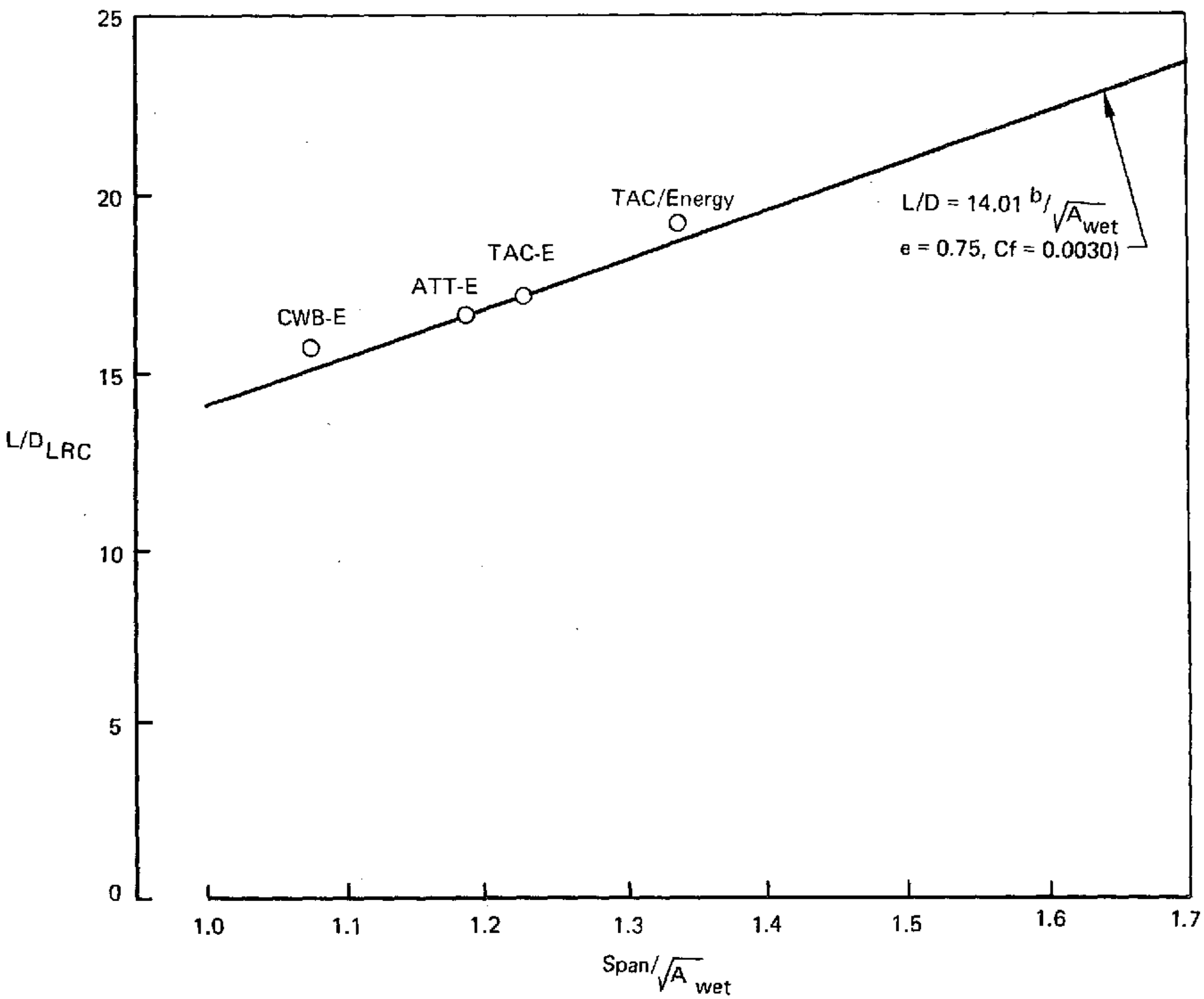


Figure 106.—Effect of Wetted Area and Span on Cruise Efficiency

Range = 5 556 km (3 000 nmi)
Payload = 18 140 kg (40 000 lb)

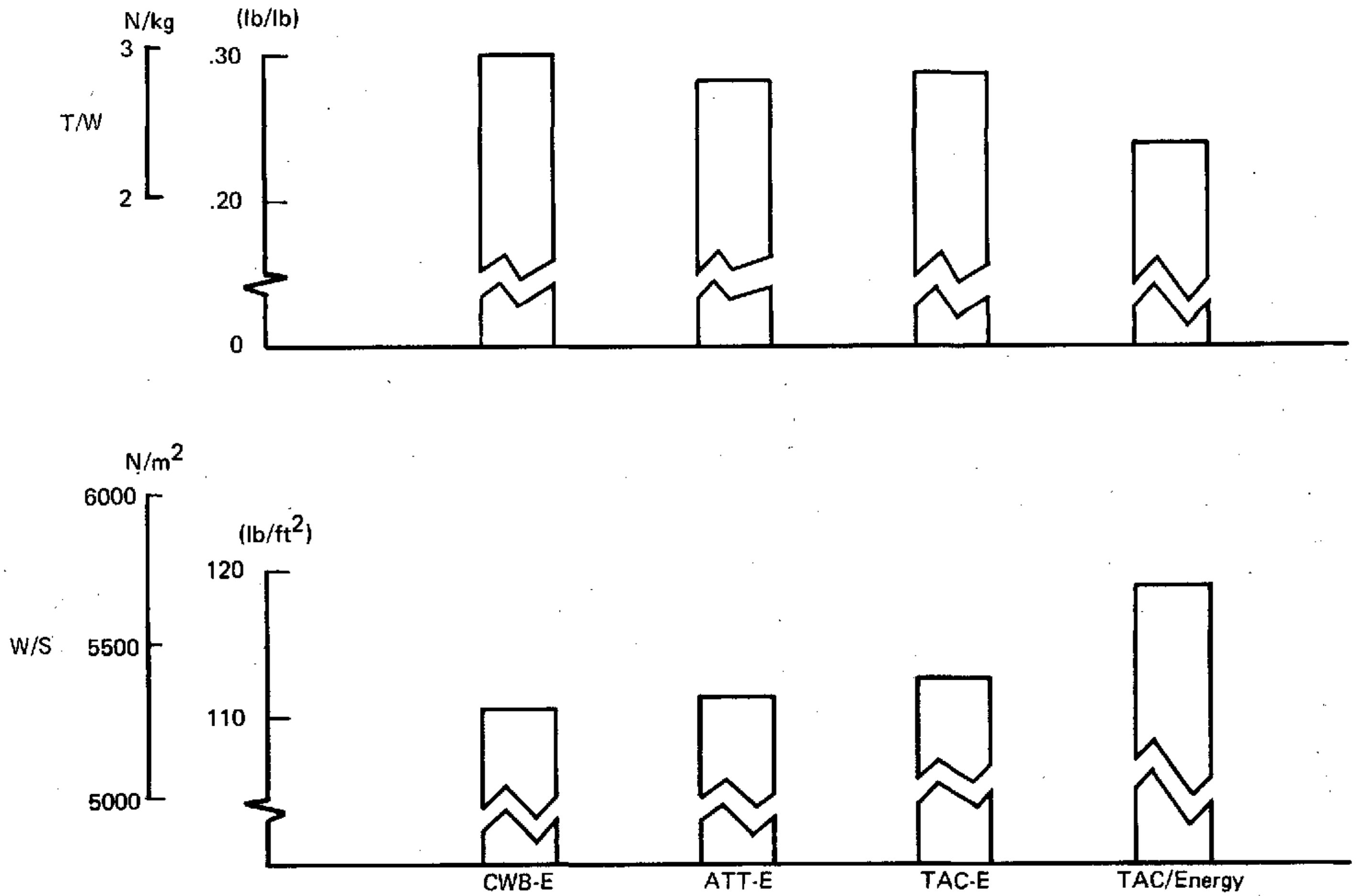


Figure 107.—Engine and Wing Size

6.2.2.3 Low-Energy Impact on Noise

Figure 108 shows that the TAC/Energy airplane gave up some noise reduction potential on the FAR 36 3° approach and cutback but is quieter on the sideline. In particular, the TAC-E achieved a quieter 3° approach and cutback noise than the TAC/Energy. The TAC-E engine was oversized to achieve 520 m (1700 ft) over the community and to permit thrust cutback to 56%. In addition, the TAC-E used a bypass-4 engine (optimum for Mach 0.9 cruise) and inlet rings and a fan duct splitter to quiet the engine noise. The oversized engine, rings, and splitter all caused fuel penalties. To conserve fuel, the TAC/Energy uses a bypass-6 engine (optimum for Mach 0.8 cruise) with peripheral lining. However, the peripherally lined bypass-6 engine is about 2 EPNdB quieter than a similarly treated bypass-4 engine at both cutback and approach conditions and 5 EPNdB quieter on the sideline.

When noise contours and two-segment approach are considered for the different airplanes, the noise comparison changes to favor the TAC/Energy. Figure 109 shows the 90-EPNdB contour for both takeoff and approach. The takeoff area encompassed by the TAC/Energy is less than the TAC-E but the TAC/Energy 6°/3° two-segment approach area is slightly larger than the TAC-E 9°/3° approach. The net effect is that the TAC/Energy total contour area is 28% less than the TAC-E contour area. (See fig. 110.)

A further reduction of the TAC/Energy approach area could be achieved by lengthening the lined inlet to an L/D of 1.0. About 1- and 2-1/2-EPNdB reduction at cutback and approach, respectively, could be achieved. Additional reduction is possible with a sonic inlet or with inlet rings and splitter. The addition of inlet rings and splitter, at an airplane OEW penalty of about 1% and less attractive economics, would result in the 90-EPNdB approach contour shown in figure 111. The figure shows that the TAC/Energy approach contour approximates the TAC-E approach contour. Noise reduction concepts described in this paragraph would require substantial research dollars and testing to verify they are both feasible and practical.

6.2.2.4 Emissions

A summary of the emissions impact is contained in figure 112, which shows the total pollutant emissions of CO, HC, and NO_x for the EPA landing takeoff cycle for the TAC/Energy airplane. The data are compared to the previous Mach 0.9 TAC (ref. 2) concept and the TAC goals for the Mach 0.8 and 0.9 airplanes.

Various differences exist between the two airplanes shown. The TAC/Energy airplane has engines of smaller airflow size because of the decrease in cruise Mach number from 0.9 to 0.8 and improved aerodynamic data base. The TAC/Energy concept uses an APU sized for ground operations, which supplies power to the powered wheel system. The TAC airplane used two much larger in-flight operable APU's sized to provide anti-icing at the low engine thrust settings for steep (9°/3°)descents and, consequently, ran at a less efficient part throttle setting for ground operations. This difference in the APU's is responsible for the large difference in the CO emission.

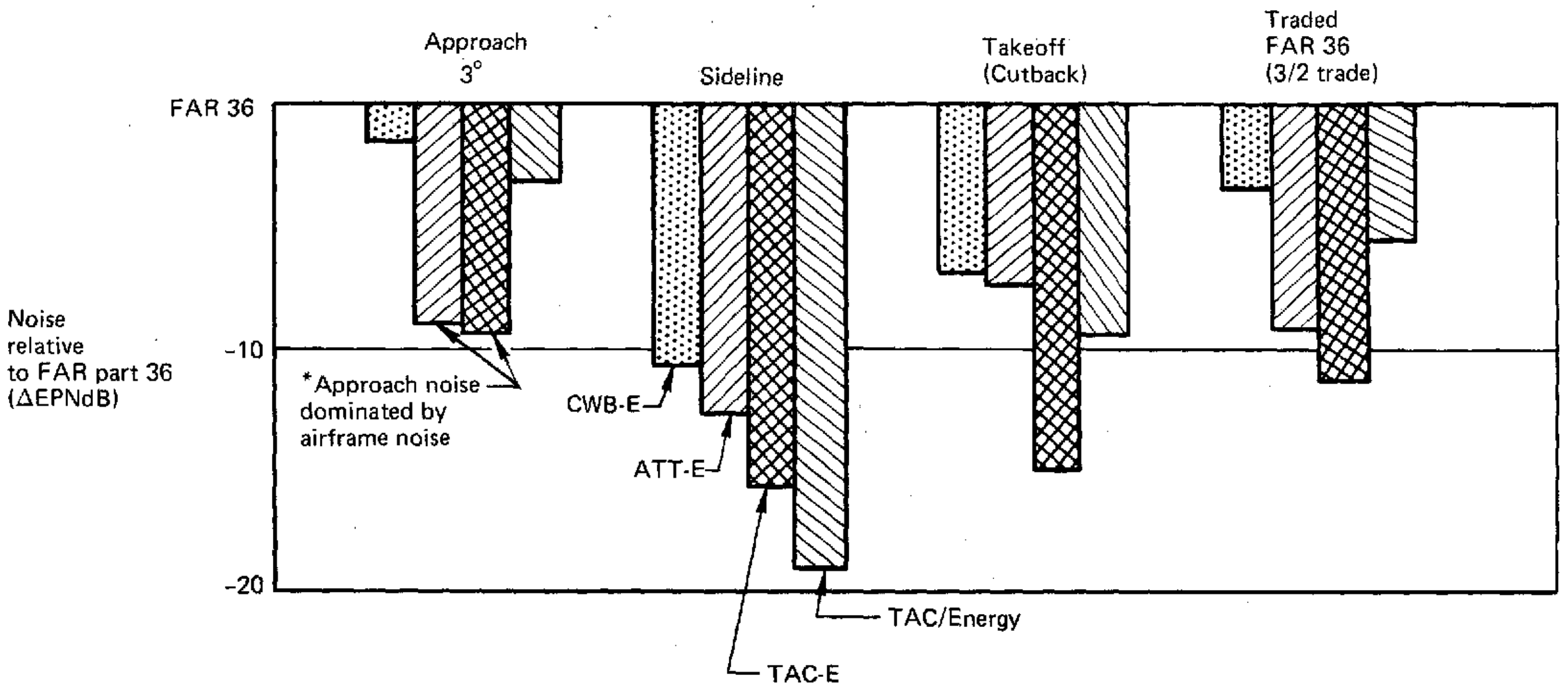


Figure 108.—Airplane Noise Comparison

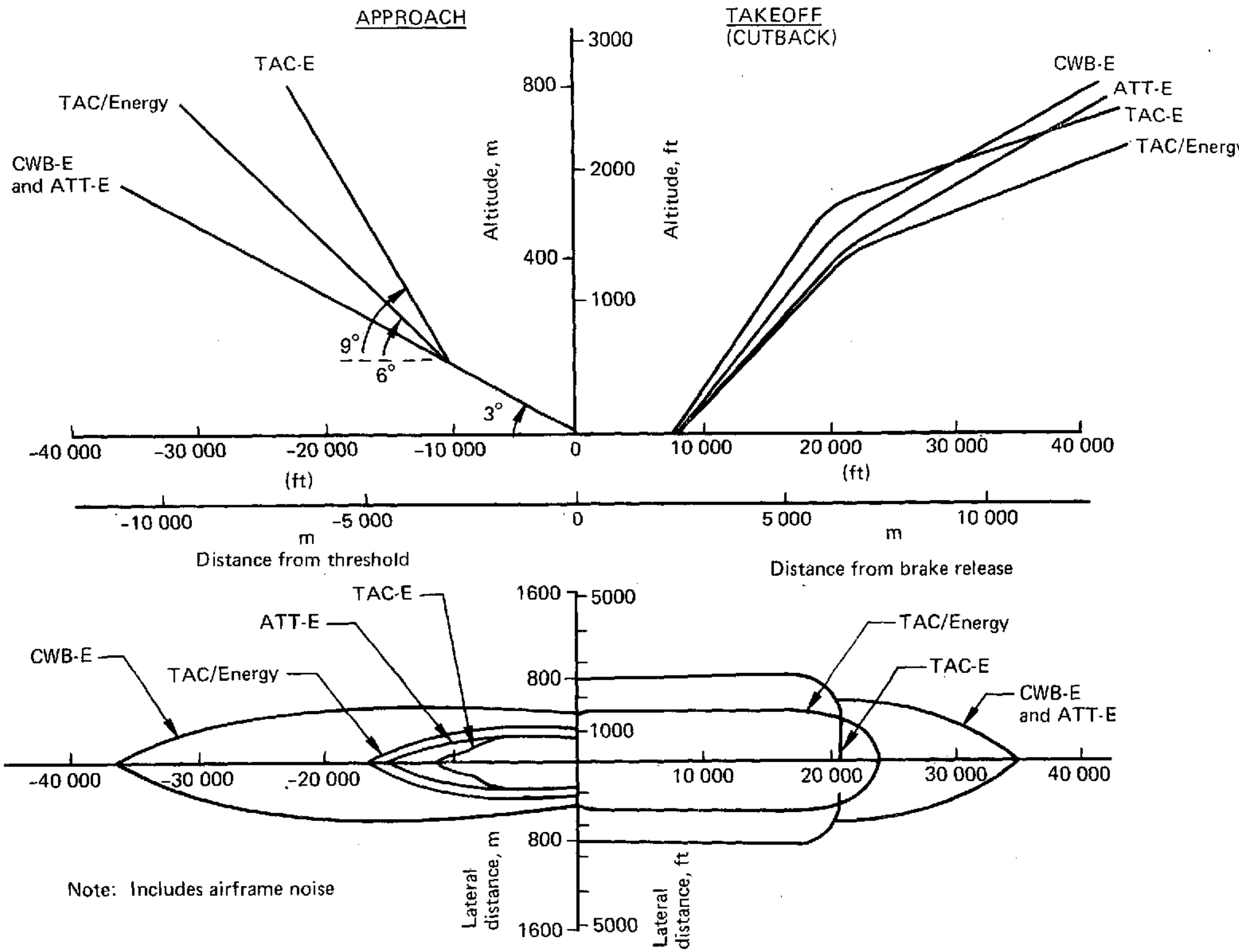
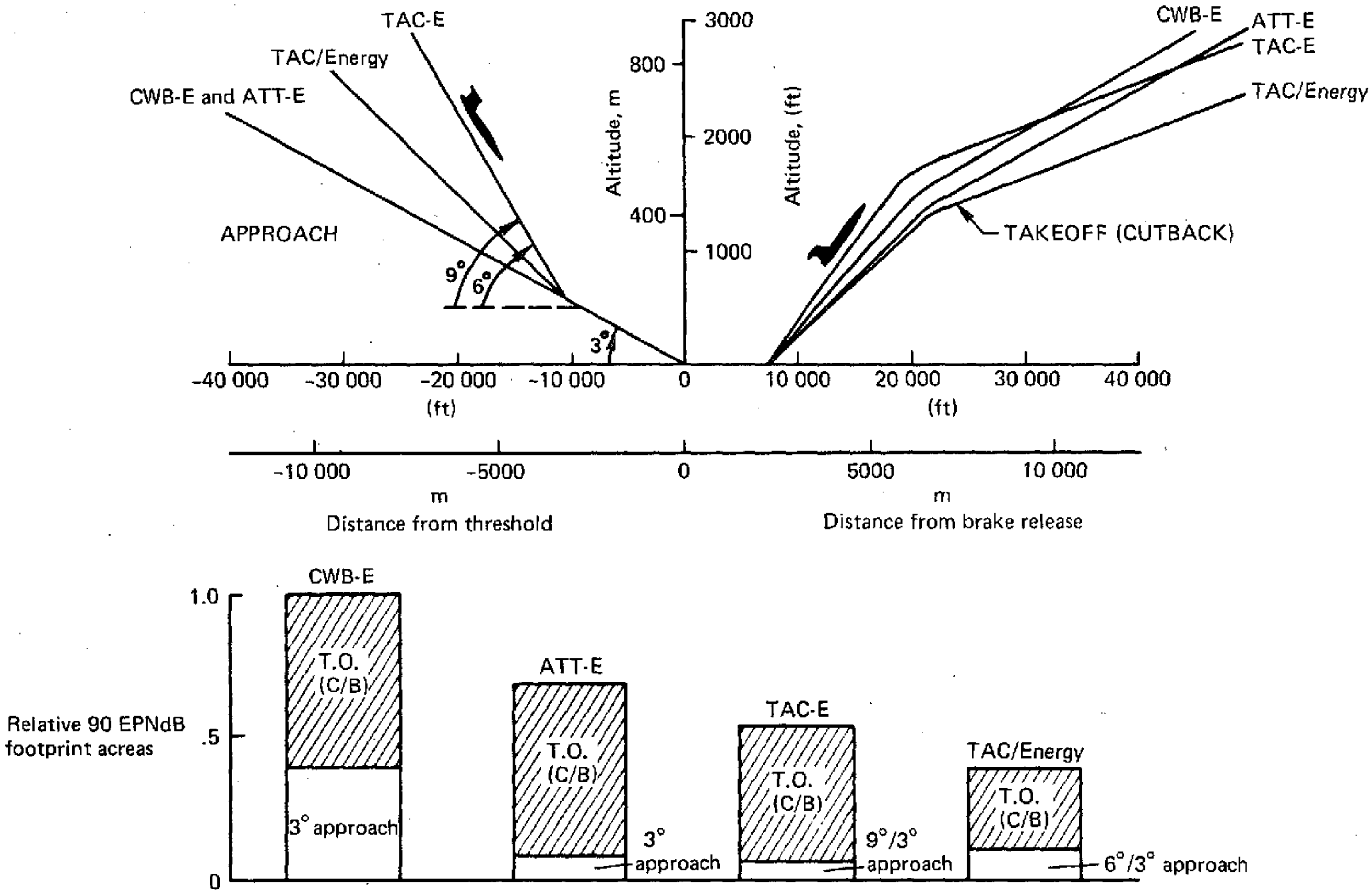


Figure 109.—Noise Footprint Comparison (90 EPNdB)



1. Base area = 5780 acres = 9.05 st mi^2
2. Includes airframe noise

Figure 110.—Terminal Compatibility/Low-Energy Benefits 90 EPNdB Noise Contour Area Comparison

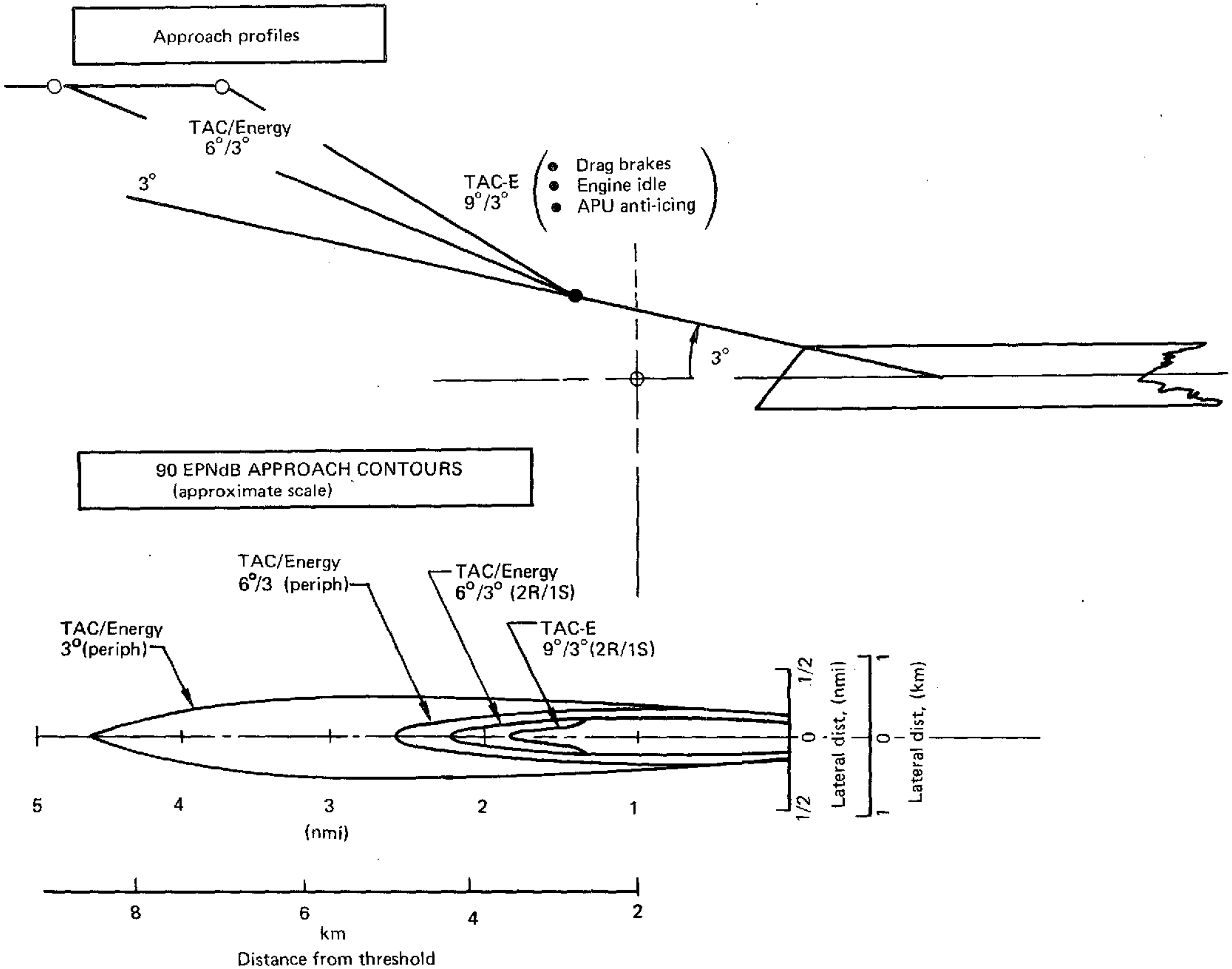


Figure 111.—Steep Descent

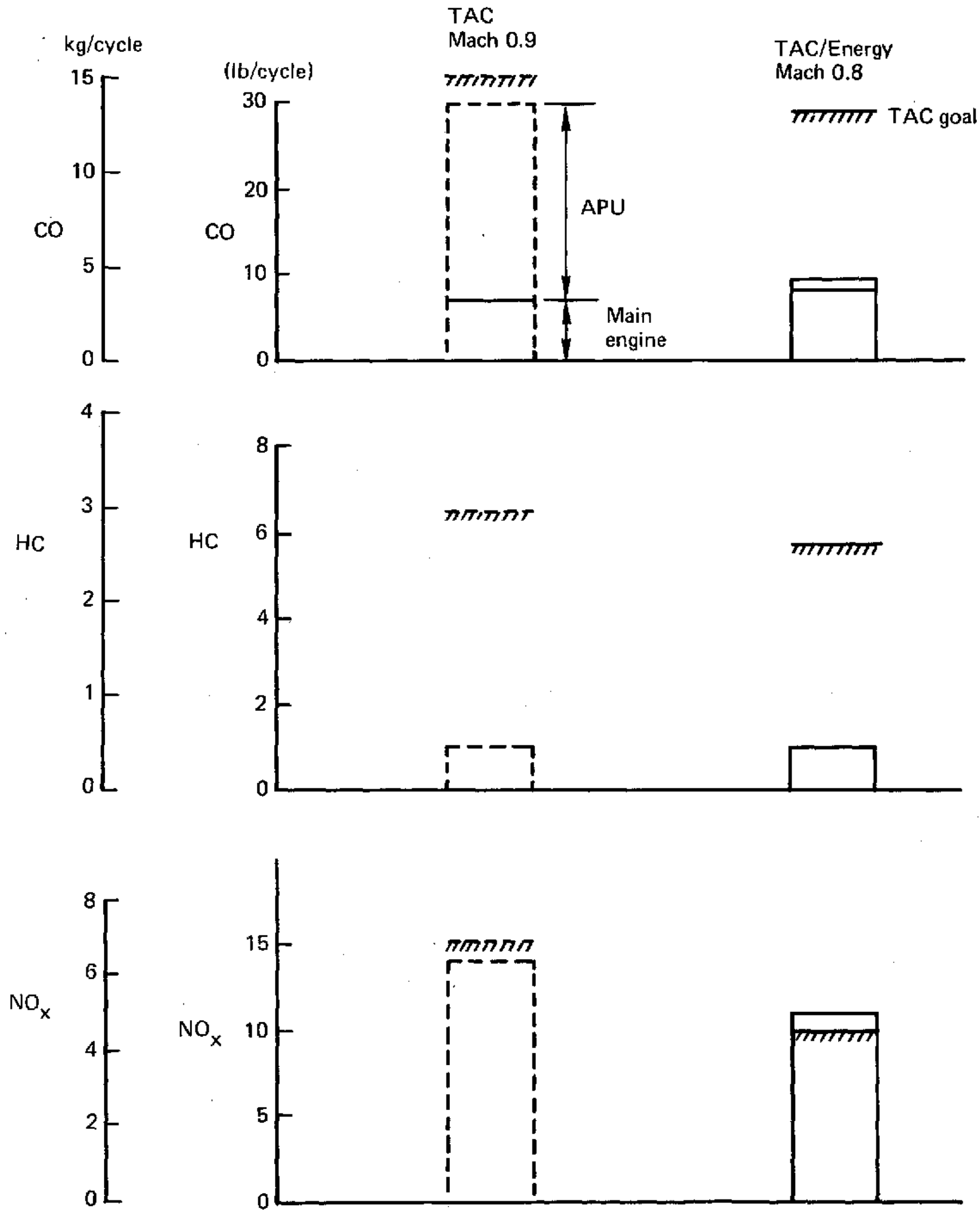


Figure 112.—Emissions Comparisons

6.2.3 ECONOMIC ASSESSMENT AND COMPARISONS

6.2.3.1 Method of Analysis

The method of calculating operating costs and the value of investment was derived after considerable discussion with the subcontractor airlines. Every effort was made to establish methods that would correctly reflect the real world sensitivity of operating costs and investment potential to technological characteristics of the aircraft concepts. Table 20 shows the basic concept used to evaluate the TAC/Energy and the comparison airplane concepts. (See sec. 6.2.3.3.)

Table 20.—Economic Evaluation Method

1. Price: \$/lb calculated on basis of study of complexity of each major assembly area
2. Crew Pay: constant \$/FH
3. Fuel Cost: fuel burned times prices 5.8¢/liter and 7.9¢/liter (22¢/gal and 30¢/gal)
4. Maintenance
   a. Airframe
      System-by-system analysis of subject aircraft compared to 727 and 747. Special studies of unlike systems
   b. Engine
      American Airlines (NASA) formula
5. Trips per Year
   American Airlines formula
6. Depreciation
   14 years to 10% residual value (includes spares)
7. Insurance
   1% of aircraft price
8. Spares
   6% of airframe price
   30% of engine price
9. Cabin Attendants
   Number is function number of seats: \$20.39/FH/attendant. Food varies with number of seats, load factor, and block time
10. Landing Fees
    Function of maximum landing weight: \$0.42/454 kg (1000 lb)
11. Passenger Related and Administrative Costs
    Constant cost on all airplanes evaluated: \$1426/1852 km (1000 nmi) flight
12. Net Present Value
    15% discount rate
    Payment made at time of delivery; computational base is year of delivery
    7% tax investment credit
    8 yr sum of digits method for calculating depreciation for tax purposes

Table 21 shows the estimated price of the TAC/Energy aircraft by major assembly areas. Development of these costs was based on the contractor's experience. They have been escalated to reflect more complex manufacturing procedures, advanced materials, or other such deviation from standard current model manufacturing procedures. A 300-airplane run was assumed. All calculations are in mid-1974 dollars. This table also indicates the recurring and nonrecurring costs as dollars per kilogram of weight.

Table 21.—Airplane Price Calculation; TAC/Energy Airplane

Costs (mid-1974 dollars)			
Cost factor	Average cost per airplane, \$M (300 airplanes)	\$/kg (\$/lb)	Nonrecurring costs, \$M
Wing	2.217	130.74 (59.32)	125.621
Body	3.368	189.74 (86.09)	211.201
Empennage	0.638	228.62 (103.73)	41.205
Landing gear	0.711	106.92 (48.51)	27.811
Nacelle	0.322	101.54 (46.07)	15.812
Power rack	1.116	456.85 (207.28)	44.453
Electrical	0.484	237.44 (107.73)	23.957
Electronics	0.955	497.86 (235.89)	19.514
Controls	0.581	234.11 (106.22)	46.125
Hydraulics/pneumatics	0.452	366.06 (166.09)	21.023
Air conditioning	0.311	201.38 (91.37)	14.480
Interiors	1.660	154.74 (70.21)	34.300
Total airframe	12.815	184.41 (83.67)	625.500
Engines	2.344		
Total	15.159		

Crew pay was calculated on a constant dollar per flight-hour basis for all airplanes being compared. A value of \$275 per flight-hour was used as the constant. This is above current average airline crew pay, chosen to reflect the likely level for this capacity aircraft and with the assumption that it would be the prime route choice aircraft.

Fuel price is simply fuel burn times price per unit. To evaluate the effect of potential future fuel prices, two values, 5.8¢/liter (22¢/gal) and 7.9¢/liter (30¢/gal) were used. Results are shown at both fuel prices.

Depreciation and insurance were calculated on an annual basis and allocated to the average trip being evaluated. The estimated number of similar trips per year obviously has significant effect on this allocation. American Airlines studied this problem and derived a formula for calculating trips per year. (See sec. 4.6.2.) This formula was used except that by ground rule no change in trips/year was indicated as the result of change in cruise velocity of less than Mach 0.03. Depreciation was calculated on the airplane plus spares. Spares were estimated to be 6% of the airframe price and 30% of the engine price. Depreciation was calculated assuming a 14-year life of the airplane to 10% residual value. Insurance was based on the airplane price and estimated at 1% per year (estimated to be an average over the life of the aircraft). Using the same procedures as the previous TAC study, a special study was made to calculate airframe maintenance costs. The airframe maintenance costs calculated for the

CWB-E, ATT-E, and TAC-E concepts were updated to reflect higher (1974) labor rates and inflated material costs above those estimated in reference 2.

The TAC/Energy transport airframe maintenance was calculated in a manner similar to that used in reference 2. Hourly and cyclic maintenance costs on a system-by-system basis were devised from CAB-reported data relative to current transport maintenance. Airline data available to the contractor were used to allocate costs not only on an hourly and cyclic basis but also by the division between labor and materials on each system. As a result of the updated information from reference 2 and this study, all four concepts were evaluated comparing each system with the like system in current transports.

The propulsion system maintenance cost estimate used herein was derived by the method developed by American Airlines for NASA (ref. 6). This method relates the propulsion systems (ATA systems 71 through 80) maintenance costs to a repair rate and a cost of repair. The rate of repair is a function of the flight length (flight-hours per flight cycle), the operational maturity of the engine (years of operational fleet service of the engine type), and the turbine inlet temperature. The labor to remove and replace the powerplant assembly in the airplane and the labor to tear down and build up the assembly in the shop are functions of the engine size (defined by engine weight). The shop labor to repair the base engine was assumed to be 1400 manhours per shop visit for a conventional turbofan, independent of engine size. The material cost per repair was estimated to be proportional to engine price. In addition to the engine maintenance, an estimate for the thrust reverser and starter systems, both proportional to flight-hours, was included.

The accounts listed as "indirect operating costs" (IOC) in the ATA formula were divided into those which were passenger-related and those which were airplane-related. Flight attendant costs were calculated as constant dollars per flight-hour, the number of attendants varying with the first-class and tourist seats in the aircraft but not varying with load factor. Food costs were calculated as a function of aircraft seats and the assumed load factor, these costs varying with block time for the trip. Aircraft servicing was calculated as a function of gross weight. It is recognized that aircraft of the same general size but with differing weights will probably require the same servicing. However, the amount is small and it was decided to accept this deficiency rather than make a study to determine a better criterion. Landing fees were calculated as a function of maximum landing weight to reflect differences between aircraft of differing size and landing weights.

Ground facilities were handled as a special case. All concepts except TAC-E and TAC/Energy were charged a constant cost per trip per ground facilities. A small deduction from this account was made to reflect the advantage of powered wheels in the TAC-E and

TAC/Energy type concepts, assuming elimination of the requirement for tugs to push the aircraft back from the gate. Estimate of the value of this saving was made with allowance for a backup tug being available.

All other accounts were held constant for all concepts. A representative number, estimated from previous work with the Boeing-Lockheed IOC formula, was used.

Net present value (NPV) was calculated for each concept, using the following ground rules:

- Discount ratio = 15%.
- Payment for aircraft and spares is made at the time of delivery (no prepayments).
- Net present value is computed to the year of delivery.
- A 7% tax investment credit was allowed.
- An 8-year sum-of-the-digits method was used for calculating depreciation for tax purposes.

6.2.3.2 Economic Evaluation of TAC/Energy Airplane

Evaluation of the TAC/Energy airplane was made using the methods described in section 6.2.3.1. Based on the analysis conducted during the TAC study (ref. 2), it was assumed that all airplanes in the fleet were equipped with TAC features, with delay being held to the 6 min of air maneuver objective established by DOT. This assumption, based on the estimated capability of TAC features to reduce congestion, makes the block time of the TAC/Energy aircraft less than the higher cruise velocity comparative airplanes when all are evaluated at the expected delay level. The combination of lower fuel consumption and minimum delay gives the TAC/Energy concept a tremendous advantage from the standpoint of fuel conservation as well as airline economics. The lower fuel consumption airplane obviously pays a smaller penalty as fuel prices increase. Basic evaluation was made at a fuel price of 5.8¢/liter (22¢/gal). Therefore, the evaluation of the economics at 7.9¢/liter (30¢/gal) fuel price shows an even greater advantage when compared with the other airplanes. (See sec. 6.2.3.3.)

Figure 113 shows the distribution of operating costs for the TAC/Energy concept, indicating costs at both fuel prices. Note should be made that maintenance costs on the complex features of the aircraft are greater than fuel costs, even when fuel is assumed to be 7.9¢/liter (30¢/gal). Part of the reason for this high level of maintenance cost is a conservatism relative to maintenance of composite materials. All evidence to date shows good maintainability; however, since the sample from which the evidence is taken is small, maintenance of composites was held at a high level.

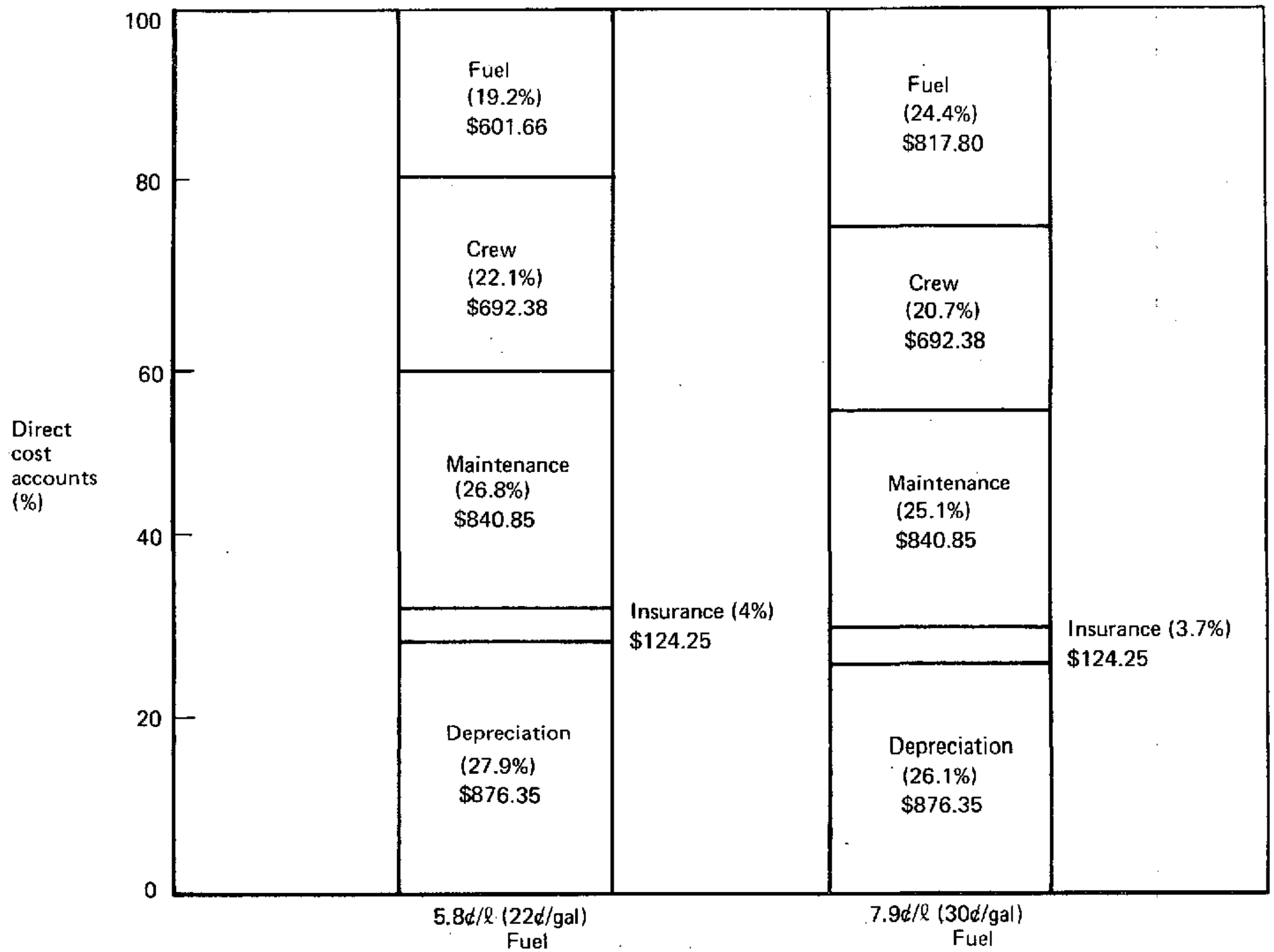


Figure 113.—Cost Distribution, TAC/Energy Aircraft [1852-km (1000-nmi) Stage Length]

6.2.3.3 Economic Comparison Between TAC/Energy and Comparative Concepts (CWB-E, ATT-E, TAC-E)

An economic evaluation was made of the TAC/Energy concept with three comparative concepts established in the previous portion of the study. Economic evaluation was made on the updated versions of these comparative airplanes (CWB-E, ATT-E, TAC-E), as described in section 6.1.2. Evaluation was made in the areas of operating costs (DOC accounts) and in the relative value of the investment in each type of aircraft.

Results are shown at two fuel prices, 5.8¢/liter (22¢/gal) and 7.9¢/liter (30¢/gal). The results are also shown under two delay conditions: (1) standard delay which provides for 6 min of air maneuver in the terminal area and (2) expected delay, which is the standard delay for TAC-E and TAC/Energy since the congestion-relieving features are estimated to increase runway acceptance rates to the point that delay will be minimal. An average expected delay of 36 min was applied for aircraft not so equipped (CWB-E and ATT-E). DOC, block fuel, and block time comparisons are tabulated in the pull-out chart on page 229.

It is recognized that a few TAC-type aircraft in a mix of aircraft operating at an airport will make little or no difference in congestion. The "expected delay" case indicates conditions when all or most aircraft are TAC-equipped, thereby minimizing congestion. The economic potential of a 30-min delay reduction is greater than the economic potential of fuel reduction, assuming fuel to be priced in the range studied.

Figure 114 shows operating costs relative to costs for the current wide-body aircraft Two scales are indicated—one a comparison with the resized CWB-E and the second a comparison with the CWB_{LRC}. When all aircraft are evaluated assuming each to have the standard 6 min of airborne maneuver, the TAC/Energy has a slight advantage in operating costs with the delta being greater when fuel price is higher, as would be expected. The basic TAC-E airplane concept has the highest operating costs when the costs of the noise reduction, emission reduction, and congestion reduction modifications are assessed with no offsetting credit being made for congestion reduction and consequent reduction in delay. The advantage of slightly higher cruise velocity, and consequently lower block time, cannot offset the higher acquisition price and higher maintenance costs. When compared to the TAC-E concept, the primary economic advantage of the TAC/Energy concept is attributable to its low fuel usage. The CWB_{LRC} is 1% to 3% more expensive to operate, varying with conditions evaluated, and therefore the percentage improvement is slightly greater in each case.

The lower part of figure 114 shows the situation for the TAC-E and TAC/Energy concepts if the TAC-type aircraft become a large portion of the fleet. These aircraft are evaluated and compared with the CWB-E and ATT-E, assuming the predicted delay for standard aircraft in future traffic situations (36-min average delay for all flights). The TAC-E now shows lower operating costs than ATT-E or CWB-E. However, the TAC/Energy concept, with benefits in congestion reduction as well as lower fuel consumption, is estimated to operate at 84% of the cost of current aircraft with a fuel cost of 5.8¢/liter (22¢/gal). Further advantage, due to lower fuel consumption, will be realized if fuel price is increased. Inasmuch as aircraft prices are not greatly different, net present value calculations follow the same patterns. See figure 115.

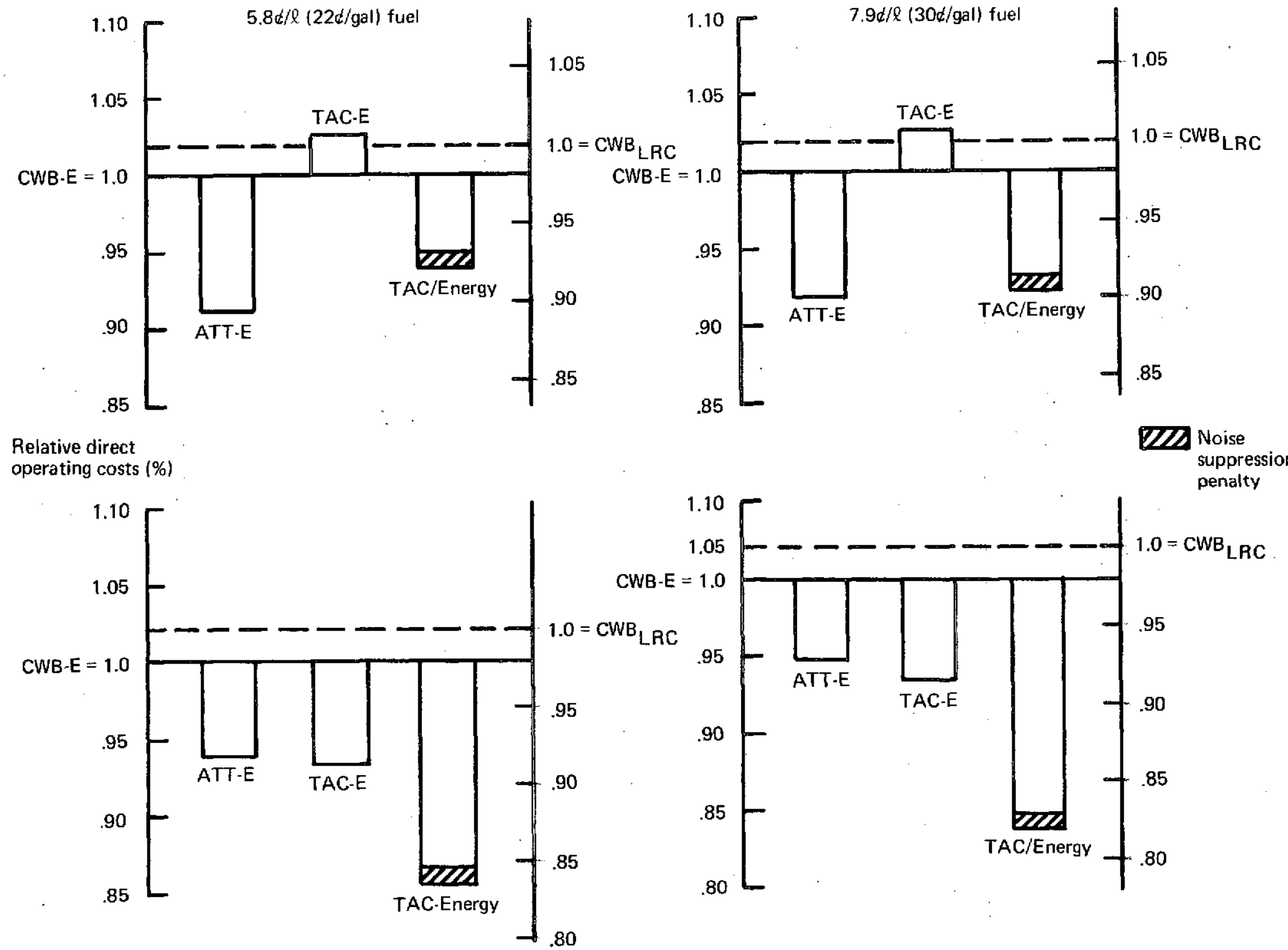


Figure 114.—Relative Operating Costs: TAC/Energy Versus Comparison Aircraft [1852-km (1000-nmi) Stage Length]

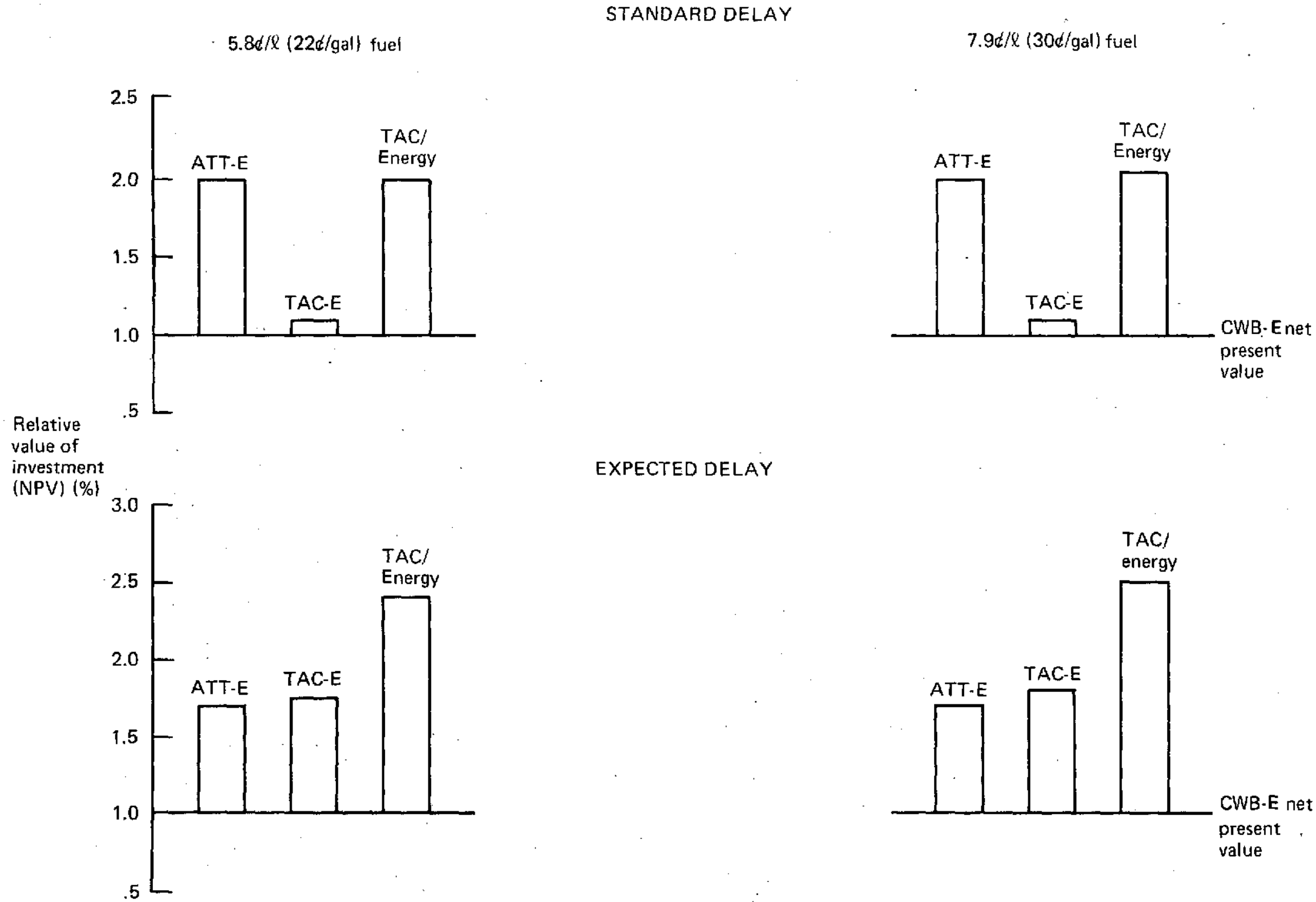


Figure 115.—Relative Value of Investment (NPV) [1852-km (1000-nmi) Stage Length]

The preceding reflects the significant potential economic advantage offered by measures to reduce delay and congestion. Important as fuel consumption reduction is shown to be, delay reduction has a greater potential economic payoff at the fuel price considered. The TAC/Energy airplane, with significant advantages in both areas, indicates the important economic payoff even though the other factors (price, maintenance, crew, etc.) are comparable or slightly higher. Figure 116 illustrates this point, showing the difference in fuel costs between TAC/Energy and CWB-E as well as differences in total operating costs. When both airplanes are evaluated at standard delay, the fuel benefits of the TAC/Energy airplane are somewhat offset. However, when there is a delay difference, the fuel that is not wasted in holding in the terminal area because of congestion reduction is significant for the TAC/Energy airplane. Because fuel was of prime importance in this study, holding fuel was calculated for all concepts at optimum speed for fuel conservation, and at an assumed holding altitude of 6100 m (20 000 ft). For all models compared, significant fuel reduction was achieved by the simple addition of a time increment as reported in reference 2 when fuel consumption was simply an economic parameter. Future study of optimum holding procedures for fuel conservation might prove to be fruitful. Without delay, the TAC/Energy operates at a lower block time than CWB-E and the advantages relative to time-oriented variables (crew, hourly maintenance, etc.) add to the total savings.

The preceding calculation assumed that no noise abatement equipment other than peripheral lining had been added to the engines. If rings and splitters are added for the purpose of reducing noise levels, a change in DOC would be expected. Fuel burn is estimated to increase 3.5% as a result of these noise abatement procedures. The hatched areas in figures 114 and 117 indicate the expected variations.

6.2.3.4 Comparative Fuel Burn

Inasmuch as the prime objective of this study is to minimize the fuel necessary to provide adequate passenger service on the United States domestic airline system, analysis was made of comparative fuel burn on a per passenger kilometer basis and also on a partial system wide basis involving several aircraft and routes. The results indicate substantial fuel savings for the TAC/Energy concept relative to current wide-body aircraft (CWB-E), even when delay is considered to be equal. Significantly greater savings occur if the TAC-E and TAC/Energy concepts are given credit for fuel saved due to minimal delay. Figure 117 shows relative fuel usage for both standard and expected delay.

Figure 117 indicates the savings in fuel consumption accomplished by the TAC/Energy airplane when compared with current wide-body aircraft. Fuel burn by a TAC/Energy airplane on an 1852-km (1000-nmi) trip is only 70% of that consumed by the CWB-E, even when delay is assumed to be the same for both aircraft. If compared to the CWB_{LRC}, the TAC/Energy airplane uses 68% as much fuel as this airplane. When the TAC/Energy airplane is credited with the delay reduction estimated for fleets of TAC-equipped airplanes, the fuel burned drops to 64% of that burned by CWB-E with its expected 36-min average delay. If comparison is made with the un-resized CWB_{LRC}, the fuel burn of the TAC/Energy airplane is 62% of CWB_{LRC} when both delay reduction and lower fuel consumption are considered.

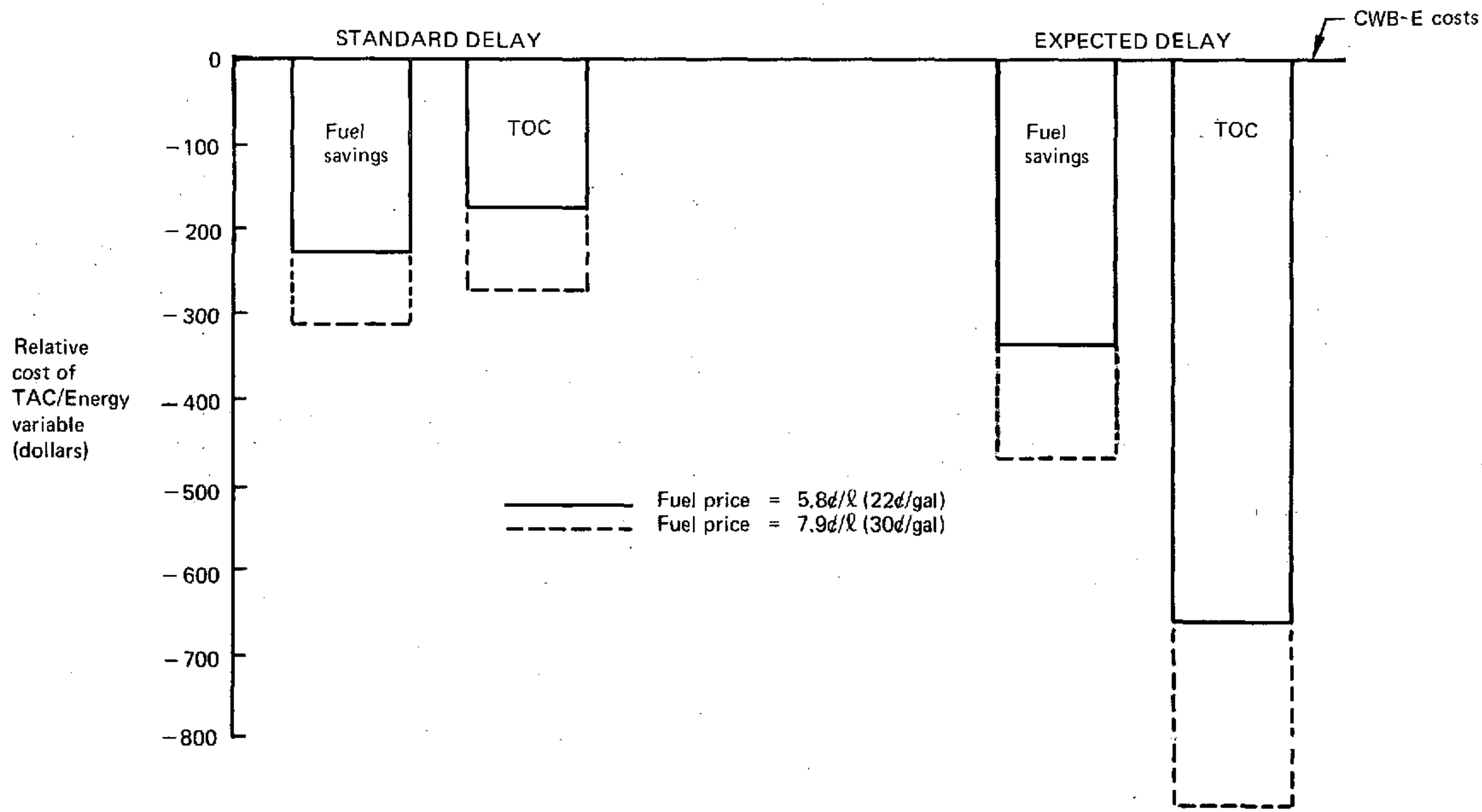


Figure 116.—Economic Advantage of Fuel Reduction and Delay Reduction—TAC/Energy Airplane

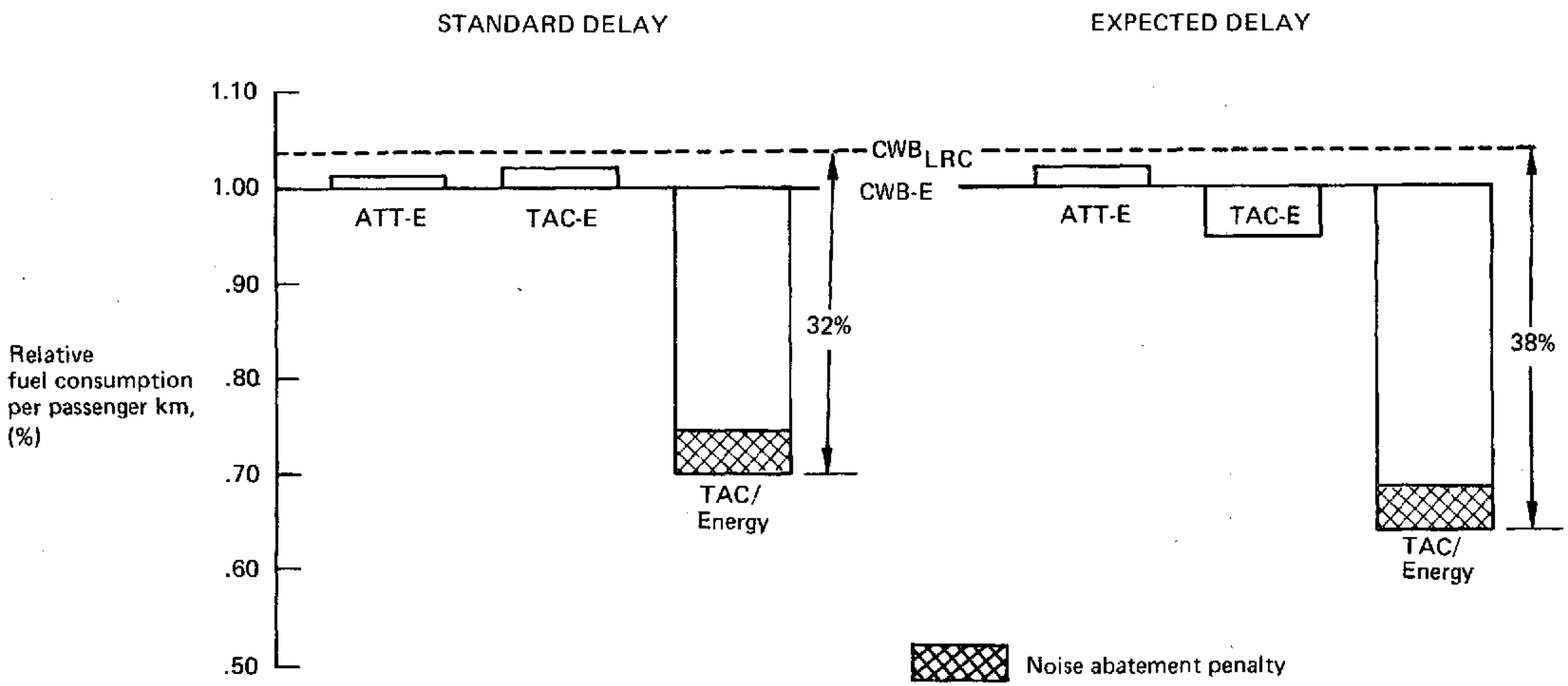


Figure 117.—Relative Fuel Consumption Per Passenger Kilometer [1852-km (1000-nmi) Stage Length, 55% Load Factor]

6.2.3.5 Comparative Fuel Burn on a System Basis

Comparisons of fuel consumption and block times were made using the current United Air Lines DC-10 route structure as a basis for comparison. Actual July 1974 schedules were used to determine the block times. Allowance for delay varies as a function of place and time of day. These block times were used for the system labeled as CWB-E.

Block times for the comparative aircraft (ATT-E, TAC-E, and TAC/Energy) were derived from computer computations. Expected delay, 36 min, was calculated for ATT-E since this aircraft has no delay-reducing features. TAC-E and TAC/Energy airplanes are given credit for reducing delay down to the standard 6 min of air maneuver. Therefore, block time for these airplanes was calculated with the expected lower level of delay. Calculations of block time for all of the comparative airplanes used the system average for delay and applied it equally at all airports and at all times of day.

Block times were not significantly different between the slower cruise velocity TAC/Energy airplane and current schedule times. An exception was on nonstop transcontinental flights where time differences in excess of 30 min are observed in spite of allowance for reduced delay. In summary, reduction in delay allows the TAC/Energy airplane to operate at lower block times on ranges up to approximately 1852 km (1000 nmi). Block times are approximately equal on ranges between 1852 and 3700 km (1000 and 2000 nmi) and longer on ranges in excess of 3700 km (2000 nmi).

Fuel burn savings for the TAC/Energy airplane are impressive. (See fig. 118.) Fuel savings of 272 000 kg (600 000 lb) per day may be realized for the 25-airplane portion of a major airlines total fleet, even if no credit is given for delay reduction. When calculated on an expected delay basis, savings mount to 386 000 kg (850 000 lb) per day on this system. The TAC/Energy aircraft concept serving this system, with minimal delay, would use only 70% of the fuel current wide-body aircraft use in flying the same routes. This system total varies from the per passenger total shown in figure 117, because the routes covered vary from a short 254-km (137-nmi) route from Portland, Oregon, to Seattle, Washington, to the longest from Washington, D.C., to Los Angeles, California (4890 km, 2639 nmi). Savings vary from essentially zero to 8000 to 9000 kg (17 000 to 18 000 lb) per trip.

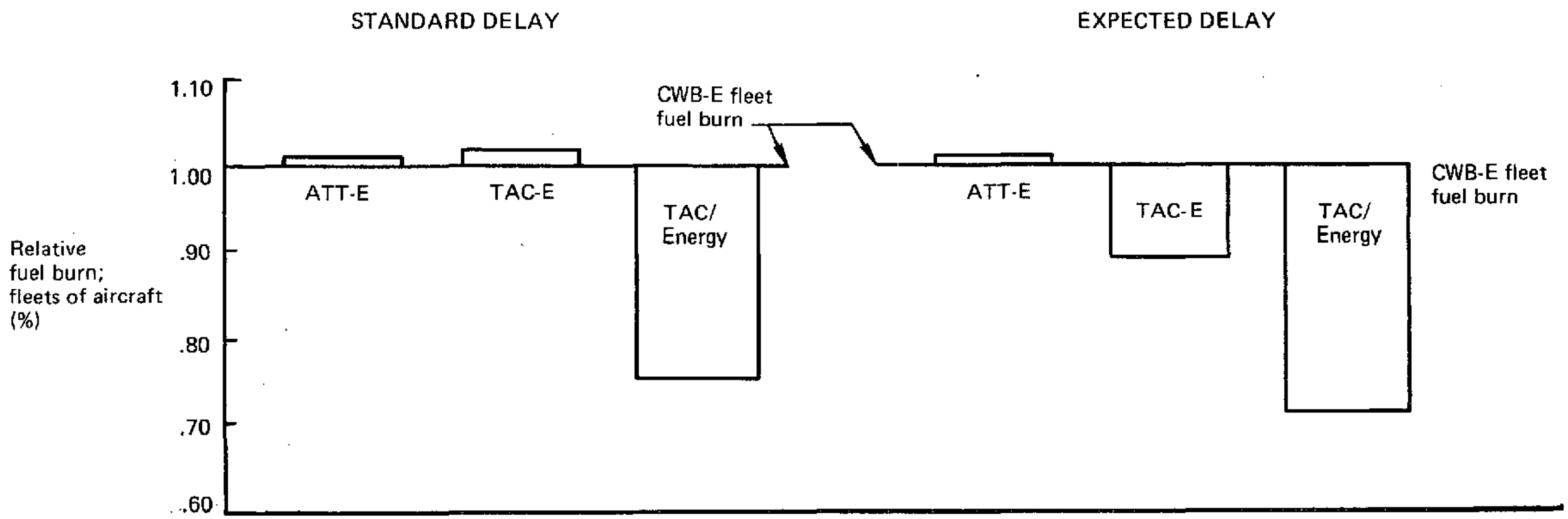


Figure 118.—Comparative Fuel Burn on a Representative Route System

7.0 CONCLUDING REMARKS

The TAC study (ref. 2) forecast expected unconstrained air traffic growth and the potential impact on airplane and airport compatibility to the year 2000. The emphasis of that study was on reducing congestion, noise, and emissions. Technical and economic assessments were made of the design modifications that were proposed in that part of the study. This present TAC/Energy study was limited to airplanes with four engines on the wing. With reducing fuel consumption as the major objective, but with attention to the concerns of the TAC study, the following conclusions can be made relative to a 5556-km (3000-nmi) range, 18 140-kg (40 000-lb) payload transport:

1. If all of the calculated potential can be realized in an acceptable design, an advanced technology aircraft designed for fuel conservation and terminal area compatibility may achieve a 30% reduction in fuel use compared to a current technology wide-body concept sized and operated at long-range cruise. It is estimated that this could erode to as low as 23%, as the design proceeds to production status acceptable to operating airlines. To achieve this reduction, it will be necessary (1) for the aircraft to contain a substantial percentage of lightweight advanced composites in the structure; (2) for new wings to be developed with aerodynamics based upon the most advanced airfoil data; (3) for the airplane to be designed with full-time stability augmentation; (4) for a new advanced, quiet and efficient turbofan engine to be developed; and (5) for the airplane to be designed to a lower cruise speed.

2. If flight delays could be reduced, the fuel reduction would increase to 36%. This would require an efficient, practical, and safe solution to the problem of trailing vorticity, assuming that the solution would not have any adverse effect on fuel consumption.

3. Of items 1 and 2, the largest single improvement (approximately two-thirds of the total) hinges upon advanced airfoils. The best way to exploit advanced airfoils for lower fuel consumption is to apply them to thin (8%) wings of moderate sweep and rather high aspect ratio. Such wings would tend to operate at higher altitudes and significantly higher lift coefficients than current wings. This aspect needs special verification with wind tunnel data and perhaps also full-scale flight data.

4. The best engine for fuel consumption is a moderate bypass ratio conventional turbofan with BPR of about 6. Noise treatment should be limited to only peripheral lining and all inlet obstructions such as rings or splitters should be avoided as extremely costly in fuel use. Advanced turbofan engines with such features as very high OPR or variable pitch or camber fan blades are not well enough understood at this time to be recommended. The application of regenerative engine cycles to aircraft propulsion still requires the invention or development of a very lightweight efficient heat exchanger.

5. Today's turboprop engines will not yield an airplane with low fuel consumption. To achieve a fuel consumption reduction with a turboprop engine, a new lightweight and efficient design will have to be developed and the aircraft speed reduced to Mach 0.6. Even though fuel reduction then occurs, the economic penalties (DOC) may be significant.

6. A very large reduction in fuel consumption can be calculated if it is assumed that the public will accept flying in very large airplanes (500 seats or more) operated at near capacity levels.

8.0 RESEARCH AND TECHNOLOGY RECOMMENDATIONS

A continuous evaluation was made of the technologies involved throughout the study, particularly during the definition of the candidate TAC/Energy concept. This allowed identification of the advancements that would be required to make similar fuel conservative concepts available in the future. The TAC/Energy concept was defined on the basis of an assumed 1985 operational introduction date. This was done by applying technologies that, with adequate R&T, were believed to be achievable by that time, while recognizing that even further identified advancements would also be beneficial during a later operational period.

The candidate TAC/Energy concept definition relied on two categories of potential technology advancement: (1) those defined during the previous ATT and TAC studies and (2) the additional advancements required to support unique design approaches to fuel conservation, the focus of this study. The contributions of the first category (ATT and TAC) were significant. Assuming the fuel conservation objectives of this study are important to the future of United States aviation, then the results of the study provide a basis that is even more significant than previously established for pursuit of recommendations made during the ATT and TAC system studies. Table 22 lists the individual R&T program recommendations that resulted from this study.

Table 22.—TAC/Energy Recommended R&T Program Subjects

- Aerodynamics Technology—Wing design and drag prediction
- Propulsion/Noise Technology
- Systems Technology—Reduced inflow dabin air-conditioning system
  —Energy conversion techniques
- Operational Techniques and Requirements—Airplane/ATC interface
  —Fuel reserves
  —Short range aircraft

The following paragraphs provide summaries of applicable technologies and the recommended advancement R&T programs significant to fuel conservation, which are related to the ATT and TAC system studies, as well as those unique to this study.

8.1 ATT STUDY RELATED RECOMMENDATIONS

The basic ATT system studies were directed primarily toward the cruise portion of the flight profile of long-range transports and to noise reduction in the terminal area. The high subsonic/transonic speed regime was emphasized. It was found that weight reduction and aerodynamic/propulsion efficiency, together with noise reduction techniques, were important to meet study objectives. The same fundamental needs are important to the TAC/Energy concept, although at a lower cruise speed.

The R&T recommendations that resulted from the ATT studies are listed in table 23 and are detailed in reference 8. Table 23 is coded to indicate the individual ATT technology advancement recommendation items that, if pursued, would also benefit fuel conservation.

Table 23.—Principal R&T Recommended Work Packages Resulting From the ATT Study (Ref. 9)

	1	2	3	4	5	6	7	8	9	10	Total (Dollars in millions)
Design integration											
Configurations											
● Low noise/congestion configuration	1.75										1.75
R&D configuration integration	2.0	2.0	2.0	2.0	2.0	2.0	1.0	1.0			10.0
● Maintenance and delay reduction	0.1	1.5									1.6
Subtotal	3.85	3.5	2.0	2.0	2.0	2.0	1.0	1.0			17.35
Aerodynamic configuration											
Exploratory programs											
● Advanced airfoils	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2			9.6
High critical Mach cowls	0.8	0.7									1.5
Subsonic/transonic area ruling	0.5	0.7									1.2
● Analytical methods improved design and analysis tools	0.6	0.6	0.6	0.3	0.3						2.4
Novel design concepts	2.4	3.6	2.4	3.6	2.4	3.6					18.0
Verification programs											
"Interference free" transonic test section	1.2	0.4	1.0								2.6
● Flight/wind tunnel correlation	1.2	0.6									1.8
● Roughness and excrescence drag	0.2	0.4									0.6
Sonic boom during cruise Slightly below Mach 1.0	0.4	0.1									0.5
Subtotal	8.5	8.3	5.2	5.1	3.9	4.8	1.2	1.2			38.2
Structures and materials											
Materials processes											
● Advanced filamentary composite structure	4.15	13.92	30.56	43.94	37.24	22.29	10.12	5.02	0.92	0.33	168.49
● Bonded aluminum structure	0.8	8.2	6.9	3.0							18.9
● Improved corrosion protection	0.08	0.01									0.09
● Titanium structure	—										
● Improved steel structure	—										
● Load alleviation											
● Integrated active control system	1.90	2.0	2.73	1.25							6.9
● Improved analysis and design capability	2.0	2.0	1.0	0.50							5.5
Subtotal	7.93	26.13	41.21	48.69	37.24	22.29	10.12	5.02	0.92	0.33	199.88

● These items also offer fuel conservation potential.

Table 23.—(Continued)

	1	2	3	4	5	6	7	8	9	10	Total (dollars in millions)
Power systems											
● Propulsion system demonstration	3.0	2.0	3.0	32.0	45.0	50.0					135.0
● Cycle selection											
Engine cycle impact	0.25	0.25	0.12	0.12	0.12	0.12	0.12	0.12	0.12		
Turbomachinery noise	3.0	3.0	3.0	3.0	3.0	3.0	3.0	1.0	1.0		50.0
Jet noise	3.0	3.0	3.0	3.0	3.0	3.0	3.0	1.0	1.0		
Improved propulsion controls	0.12	0.12	0.20	0.28	0.28	0.28	0.28	0.32	0.32		
● Optimized nacelle											
Inlet development	0.68	0.68	0.80	0.80	1.25	1.25	1.25	1.25	1.25		
Nacelle configuration development	0.36	0.36	0.80	0.80	1.30	1.25	1.35	1.25	1.25		
Nozzle development	0.06	0.06	0.40	0.40	0.48	0.48	0.88	0.88			
Thrust reverser development	0.32	0.32	0.40	0.40	0.44	0.44	0.80	0.80			47.0
Acoustic lining development	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		
Optimized nacelle development	0.10	0.50	0.50	0.50	0.50	0.50	0.50	0.50			
● Nacelle/airplane integration											
Nacelle/airplane development	0.28	0.56	0.56								5.0
Optimized nacelle development	0.22	0.56	0.56	0.66	0.60	0.50	0.50				
Community ramp and interior noise	3.0	3.0	3.0	3.0	3.0	3.0	3.0	1.0	1.0	5.0	23.0
Auxiliary system											
Hydraulic systems	1.72	2.60	3.35	2.66	1.85	0.58					
● Pneumatic, conditioning, and protective systems	0.39	0.27	0.20	0.21	0.12						
Electrical power and distribution	0.60	1.60	1.40	0.20							
● Powered wheel	0.20	1.20	0.60								
● Landing gear	0.60	0.76	0.80	1.69	0.54						35.77
Integrated engine generator	0.38	0.90	1.50	1.75	2.00	1.50	0.25				
Fuel systems	0.73	0.47	0.42	0.17							
● Carbon brake	0.25	0.52	0.58	0.15							
Subtotal	21.35	28.73	27.28	53.79	65.48	67.95	16.78	10.12	7.94	0.16	295.77

Table 23.—(Concluded)

	1	2	3	4	5	6	7	8	9	10	Total (dollars in millions)
Control of flight											
Flight controls											
● Application of load-alleviating controls to configuration optimization	See structures and materials integrated active control system.										
● Application to CCV philosophy	0.25										0.25
Transonic trailing-edge controls development	0.20	0.05									0.25
Development of improved atmospheric models for mesoscale turbulence discrete gusts	0.20										0.20
● Flightpath control system development	0.10	0.10									0.20
● Improved aeroelastic methods for flight controls analysis	0.10										0.10
● Avionics											
Advanced navigation systems development	1.60	4.00									5.60
Advanced digital systems application	1.00	1.10									2.10
Advanced flight deck development	0.75	1.15	1.70	3.10	0.10	0.10					6.90
Low-cost inertial sensors/systems	0.20	1.50	0.75								2.45
ATC/operations											
Airplane requirements	0.93										0.93
Subtotal	5.33	7.90	2.45	3.10	0.10	0.10					18.98
Total	46.96	71.56	78.14	111.89	108.65	97.14	29.15	17.34	8.86	0.49	570.18

Key items that were relied on during definition of the TAC/Energy concept are described in the following paragraphs under headings that reflect the thrust of their impact on fuel conservative aircraft.

8.1.1 AERODYNAMIC EFFICIENCY

Under "aerodynamic configuration," table 23 lists several exploratory and verification-type programs that are directed toward improved aerodynamic performance. When modified to the speed regime of this study, a majority of those programs would benefit future fuel conservative aircraft designs. This was borne out by the results of the wing planform sensitivity study when it was found that aerodynamic data on improved airfoil/wing designs were badly needed. Specific recommendations on this subject are covered in section 8.3.

8.1.2 PROPULSION EFFICIENCY AND NOISE REDUCTION

The ATT study identified several propulsion design areas (listed under the "power systems" heading in table 23) that were postured toward reduced SFC, noise, and nacelle drag. Similar improvements are needed for fuel conservation for engines at BPR's of 6 to 7, rather than at 4 for the ATT. The objective of noise reduction is somewhat in conflict with fuel conservation objectives because of inherent weight and complexity increase associated with noise reduction techniques. However, if low noise objectives are also important for fuel conservative designs, then much R&T is needed to minimize the impact.

8.1.3 WEIGHT REDUCTION

Significant weight reduction potential was identified in two major areas during the ATT system studies.

The first study, advanced structures (including composite materials, bonded aluminum, and improved steel alloy), offers from 10% to 25% reduction in the structural weight of future aircraft. The TAC/Energy concept is based on achieving the 10% reduction by a 1985 operation date. In addition, composite structure is particularly adaptable to the high aspect ratio wing type of design used on the TAC/Energy concept. Its use reduced the wing flutter penalty that was found to exist on the aluminum structure version. An additional 3% reduction in fuel use could be attained for a later airplane when technology is available to support the 25% structural weight reduction value. It is recommended that the NASA structures program that is now underway be continued and expanded to cover all aspects of the program during the ATT program (ref. 8).

The second study, advancement of active controls technology, was directed toward proving the avionics, hydraulics, and overall controls systems associated with stability augmentation systems as well as load and flutter alleviation. The stability augmentation system will allow flight under aft stability loading conditions and will provide the reduced drag that was assumed on the TAC/Energy concept. The high AR wing included on concepts similar to the TAC/Energy will be subjected to high wing root bending moments and will be more susceptible to flutter. Such designs may benefit from load and flutter alleviation type, active controls. NASA is encouraged to continue and expand the current active controls program, now underway, in a manner that will yield the technology confidence required by the airline and airframe industry to permit its adoption.

8.2 TAC STUDY RELATED RECOMMENDATIONS

The TAC system study was directed toward the reduction of congestion, noise, and emissions in the terminal area. The TAC/Energy concept incorporates most of the features defined by that study. This was accomplished with some negative impact on weight. However, this study confirmed the conclusions revealed in the TAC study that, on an overall basis, many of the features actually contributed to fuel conservation when they were included in the basic design. This was particularly true for the high AR wing and the powered wheel which were included to meet noise and emission reduction objectives, respectively. All facets of the TAC concept that were related to the reduction of congestion will be vital to fuel conservation as traffic increases in the future. The objective, of course, is to hold operational delay to a minimum which in turn will minimize fuel consumption, by decreased holding and increased runway acceptance rates. Needed key features include a high-energy brake system, high-speed turnoff landing gear, and the advanced avionics required for improving the airplane/ATC control loop to permit low-tolerance position accuracy, touchdown dispersion, and, of major significance, the reduction of separation distance between parallel runways.

The subject of wake vortex dissipation is of particular importance to congestion reduction. Based on broad theoretical models, vortex dissipation methods have been proposed, and promising qualitative test results have been obtained. Although the system impact of some of these vortex dissipation methods may impose large penalties to economics and energy usage, the first step is nevertheless to find workable solutions to the problem. To date, some of the most promising results were obtained from the following:

- Differential flap for specific lift distributions
- Differential engine thrust
- Splines
- Wing fences

As was the case in the ATT studies in regard to noise reduction, the TAC study provided recommendations for R&T needed to reduce emissions through improved combustion and burners and to reduce noise through use of steep approach glidepaths. Again the objectives were at cross purposes with fuel conservation objectives because of weight impact. In a similar manner, however, if those objectives are realistic, they must be attained at minimum technical and economic cost. The R&T programs recommended from the TAC study were directed toward that end.

In summary, essentially all of the R&T recommendations resulting from the TAC study are of great importance to future transport designs that would be similar to the candidate TAC/Energy concept. A summary list of those recommendations is shown in table 24. Key items that are of particular importance to fuel reduction for the candidate concept, either

Table 24.—Principal R&T Recommended Work Packages Resulting From the TAC Study (Ref. 3)

Item	Approach	Ground operations	Takeoff	Cruise
Airplane	● 1. *Wing trailing vortex research.* ● 2. Airframe noise research and control 3. Aerodynamic drag device development 4. In-flight thrust reversers 5. *Landing guidance* ● 6. Improved anti-icing techniques ● 7. Impact of turbulence and wind shear on airplane design ● 8. *Noise-abatement approach* and landing study 9. Stopping system trades ●10. Noise treatment versus noise abatement procedures ●11. *Engine component noise research* ●12. Engine noise reduction with lining/treatment	16. Engine emission control ●17. Auxiliary power unit development 18. Tire technology 19. *Landing* gear/brake dynamics 20. Automated stopping system 21. Brake material and configuration 22. Ground steering systems 23. Reduced gate space design techniques 24. *Airframe* and engine maintainability ●25. Large payload airplane scheduling/marketing assessment 26. Aircraft maintenance monitor ●27. Powered-wheel system ●29. Powered-wheel operational assessment	●38. Reduced penalty high-lift and low-*noise concepts* ●39. Advanced low-noise engine cycles 40. Water injection systems	41. Low-cost inertial systems 42. VLF *navigation* 43. Impact of cruise Mach constraint ●44. Structural implications of outboard engine *location* 45. Weight implications of high aspect ratio wings ●46. Guidance and control integration ●47. *Secondary power system* redundancy ●48. Airplane design/energy relationship ●49. Innovative airplane concepts for TAC application 50. Advanced fuel airplane concepts (liq H_2)
Ground facilities	●13. Steep approach operational compatibility	●30. Surface traffic control		
Passenger	14. Passenger compartment and flight deck noise	31. Passenger tolerances 32. Schedule spreading incentives 33. Aircraft *interior improvements*		51. Cabin and interior noise effect of M_{CR}
Community	15. Post-1985 noise criteria	34. Ambient air quality standards review and assessment 35. Terminal area air polution model 36. Terminal area meteorology model 37. Pollution containment *attitude*		

●These items also offer fuel conservation potential.

directly or indirectly by minimizing the impact of noise or emission reduction, are noted by symbol in the figure. The programs defined during the TAC study for each item are essentially adequate from the standpoint of emphasizing fuel reduction. The current NASA Terminal Configured Vehicle program is headed in the needed direction and should be continued and expanded. NASA is encouraged to pursue the previously defined recommendations for each of the items noted in table 24.

8.3 TAC/ENERGY STUDY RECOMMENDATIONS

With energy conservation as the driving force, this study provided the framework for evaluating additional technical and operational features, as well as extensions of previously considered features. The attractive additions and extensions were found to focus primarily on the aerodynamics, propulsion, and systems portion of aircraft design as well as potential revised operational procedures that could affect the aircraft/ATC interface. Although the quantity of new technology advancement items was not large (as compared to the ATT and TAC studies), they will be vitally important to future aircraft that are designed to objectives similar to those of the candidate concept. The following paragraphs identify those items under headings that reflect the technology involved.

8.3.1 AERODYNAMICS TECHNOLOGY–WING DESIGN AND DRAG PREDICTION

8.3.1.1 Potential Payoff

Airplanes developed for low fuel consumption will tend to have lower cruise speeds and wings of higher aspect ratio and less sweep than those directed toward best economics. These characteristics lead to cruise at higher lift coefficients than current subsonic jets. Research is needed to develop the most efficient aerodynamic shapes for such wings and to establish a data base for use in further preliminary design studies.

8.3.1.2 State of Readiness

The necessary design methods and test facilities are available.

8.3.1.3 Recommended Action

A three-phase program is recommended:

- Phase I. Two-Dimensional Airfoils.–A family of airfoils should be developed by two-dimensional transonic analysis and wind tunnel testing. A set of nine airfoils is suggested, covering the range of thickness and design lift coefficients shown in table 25.

- Phase II. Three-Dimensional Wings.–A family of wings should be designed, using the airfoils developed in Phase I. The characteristics of these wings should be measured by wind tunnel testing at both on-design and off-design conditions. A recommended set of 16 wings is shown in figure 119.

- Phase III. Parametric Design Chart.—A set of design charts should be developed from the wind tunnel data. These charts would be used during preliminary design to select airfoil sections and to predict wing drag characterisitics.

Table 25.—Two-Dimensional Airfoil Matrix

t/c, percent	$M^2 C_{\ell_{design}}$		
	0.45	0.55	0.6
7	X	X	X
9	X	X	X
11	X	X	X

8.3.1.4 Cost and Schedule

The 18-month program shown in figure 120 is estimated to cost $0.5 million.

8.3.2 PROPULSION/NOISE TECHNOLOGY

8.3.2.1 Potential Payoff

A conventional turbofan with 1980 inservice technology does not have any particular advanced technology requirements. This fuel conservation study indicated that a BPR 6 turbofan provides close to optimum performance from the standpoint of fuel utilization and operating costs. Although no new engine technology requirements for 1980 inservice operation are needed, it is important during engine and airplane installation development to preserve high engine reliability and maintainability.

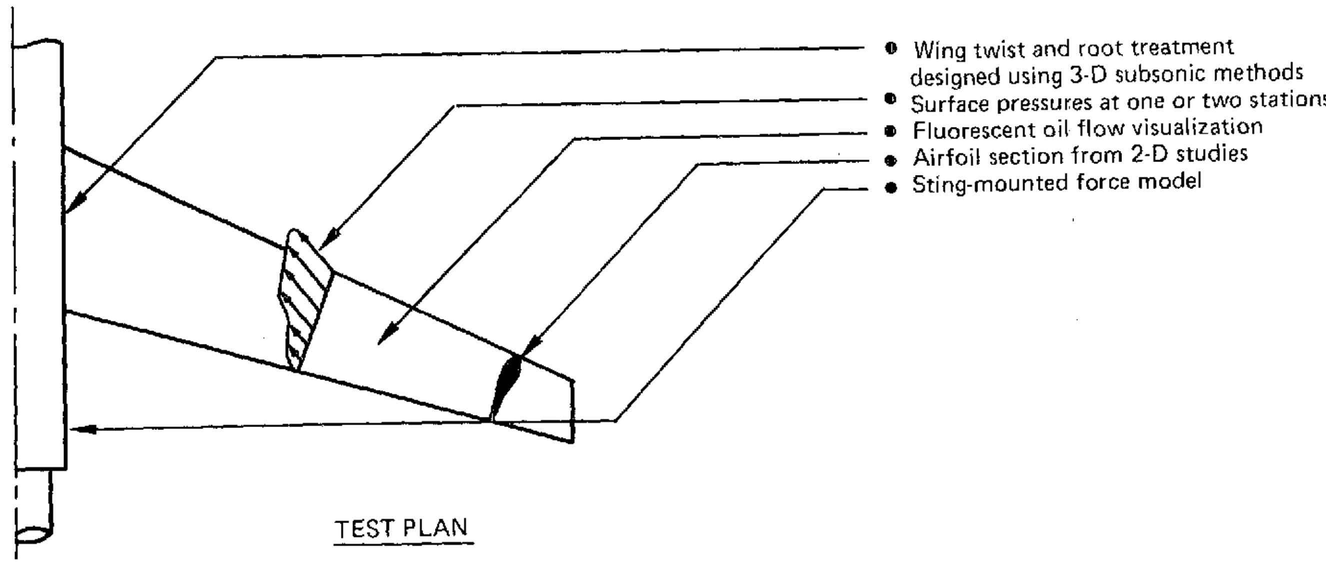
In the brief study of advanced engine cycles in this program, a single engine was not identified that was significantly superior to the conventional turbofan in fuel utilization with acceptable economics. However, high potential for energy conservation was indicated in some of the advanced cycles studied. Many additional exploratory design studies and analyses, coupled with application of advanced technology, are required to fully explore, evaluate, and validate advanced low-energy engine concepts.

8.3.2.2 State of Readiness

Since a leading candidate low-energy cycle for the post-1980 time period has not been identified, specific recommendations for technology cannot be provided. However, the following advanced technology items would improve all engines including the turbofan:

- Higher pressure ratio per stage capability at good efficiency levels, for fans, compressors, and turbines

- Improved turbine airfoil, endwall, and secondary cooling capability



Aspect ratio	Taper ratio	(t/c) %	Λ = 25°			Λ = 30°		
			2-D design C_ℓ (camber)					
			1	2	3	1	2	3
12	0.25	7	✓		✓		✓	
		9	✓	✓	✓	✓	✓	✓
		11	✓		✓		✓	
	0.5	9		✓				
	1.0			✓				
10	0.25			✓				
8				✓				

- Design C_ℓ and t/c from 2-D studies

Priority

1

2

3

4

Figure 119.—Three-Dimensional Wing Design and Test

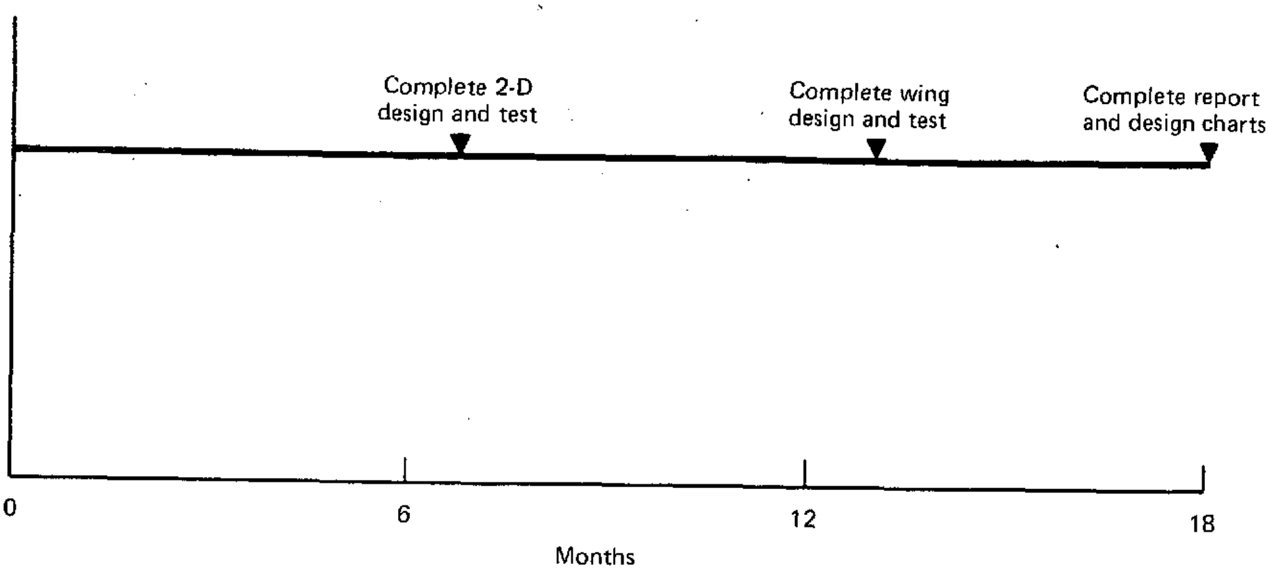


Figure 120.—Three-Dimensional Wing Design and Test Schedule

- Improved compressor, burner, and turbine durability to minimize performance degradation and maintenance costs
- Improved clearance controls throughout the engine, to improve component performance and reduce leakages and secondary flows
- Improved materials such as composite fan blades, high-temperature titanium for compressor disks, high-strength nickel base alloys for turbine disks, and high-temperature turbine airfoil materials and coatings
- Shorter burners with improved performance and low emissions technology
- Fabrication technology, including reduced-cost turbine airfoils, small cooling hole technology, near-net and net-shape disks, large cast cases, lightweight structures, and fabricated sheet metal cases
- Improved bearings; improved seals including abradable/abrasive seal technology on airfoil/cases for tighter clearance control
- Improved accessories, including an electronic control to improve performance, hot section life, control maintenance, and reliability

8.3.2.2 Recommended Action

It is recommended that engine/airframe studies be conducted that are similar to those conducted in this study but expanded to permit indepth evaluation of potential alternate approaches to given objectives, considering alternate engine cycles. Engine and airframe manufacturers should participate in the study, and both participants should be involved in establishing objectives and evaluation criteria. The airframe organization should participate to provide advisory and evaluation assistance during cycle and engine evaluation by the engine organization. Overall integrated evaluation should be conducted by the airframe organization. One or more contracts funded to a minimum of $500 000 and involving engine and airframe manufacturers is recommended.

8.3.3 SYSTEMS TECHNOLOGY

8.3.3.1 Reduced Inflow Cabin Air Conditioning System

Potential Payoff.—The airplane secondary power systems (SPS) extract up to nearly 5% of the usable energy from the airplane engine, resulting in significant fuel consumption. Of the SPS, the airplane pneumatic system is the greatest user of this energy which, during cruise, uses engine bleed air extraction to air-condition and pressurize the airplane cabin. The potential exists to reduce by at least 50% the quantity of bleed air required, with an associated reduction in block fuel of approximately 3%.

State of Readiness.—A fresh air ventilation standard of 9.44×10^{-3} m^3/sec (20 cfm) has been established for commercial jet airplanes. Under high load density conditions, this rate can be reduced somewhat, provided that proper air movement is attained. To achieve required air movement on some airplanes, unfiltered (not revitalized) recirculated cabin air is used. As the amount of fresh air is reduced and cabin recirculated air is increased, odor carryover, stuffiness, and general discomfort result. If a high degree of recirculated cabin air is to be used, it is necessary to establish guidelines as to the allowable quantities that can be recirculated without cabin air pressurization problems and the degree of filtration required to make the air physiologically acceptable.

Recommended Action.—A program to establish suitable cabin air recirculation levels is recommended. The program would consist of:

1. The analysis and testing necessary to establish recirculation air rate and filtration levels to be used on a suitable inservice airplane

2. The design of a filtration kit

3. Inservice testing of the kit to verify results of item 1

A 707 vapor cycle equipped airplane would be typical of a suitable airplane as it has a built-in recirculation system. The recirculated air is not now revitalized. Filtration would have to be added and necessary ducting changes made to allow variations in both filtration capability and recirculated airflow quantity.

Cost and Schedule.—The 18- to 24-month program (fig. 121) would cost approximately $0.15 million, not including airplane modification.

WORK STATEMENT

- Determine criteria.
- Design filtration kit and install on airplane.
- Inservice flight test.

PAYOFF

- Fuel savings from reduced engine power extraction

SCHEDULE

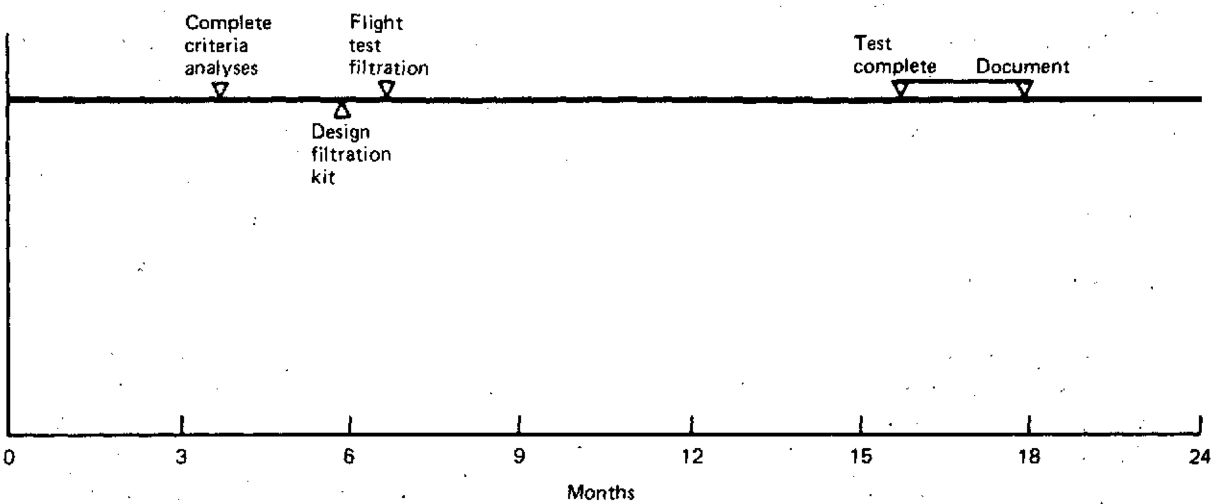


Figure 121.—Reduced Energy Cabin Air-Conditioning System Research and Technology Summary

8.3.3.2 Energy Conversion Techniques

Potential Payoff.—To accomplish the required fuel conservation required on future airplanes, it is necessary to review all energy-consuming systems and determine the most efficient means to convert fuel energy to the required airplane function. The SPS directly uses about 5% of the total airplane fuel energy to power hydraulic, pneumatic, and electric systems, and about twice that again to carry the systems weights. Considerable fuel savings could result if improved energy conversion techniques could be found that would reduce the total energy use through higher efficiency of conversion.

State of Readiness.—Secondary power systems studies have been conducted under NASA contract (ref. 9) and in conjunction with the TAC program. These studies established several areas of potential fuel savings. They include use of dedicated APU's, engine shaft power in preference to bleed, integrated engine generators, and combination generators/starters. Extension of these studies is recommended with emphasis on power conversion techniques and integration of the various power sources and functions to produce a minimal fuel consumption airplane. In particular, an independent power generation system should be explored to determine potential fuel savings benefits.

Recommended Action.—A program involving the integration of the airplane SPS energy conversion techniques is recommended. The program would explore the methods of converting fuel energy to power for the SPS (hydraulic, pneumatic, and electric) through normal engine bleed and shaft power extraction, separate power generation units, and other methods determined from the study.

Cost and Schedule.—A 12-month study funded at $250 000 is recommended.

8.3.4 OPERATIONAL TECHNIQUES AND REQUIREMENTS

A limited analysis of the flight profile conducted during the sensitivity part of the study resulted in the identification of several operational techniques that reduce fuel consumption. Some were applied directly to the TAC/Energy concept; in fact, portions are being applied to current flight operation. These include reduced climb speed, flight at long-range cruise (LRC) rather than minimum DOC cruise speed, and step climb during cruise. Other possibilities were identified but could not be applied because of regulatory constraints. The following paragraphs provide recommendations relative to these possibilities which, if followed, may involve coordinated or joint action by NASA/DOT/FAA and/or the airline/airframe industries.

8.3.4.1 Airplane/ATC Interface

Potential Payoff.—Action by the airlines with assistance by airframe manufacturers has demonstrated substantial fuel savings by application of revised operational procedures, within current regulating constraints and with no changes to the aircraft or the ATC system. Two areas were also identified—optimized altitude change as a function of gross weight and dispersed lateral spacing to accommodate aircraft with different optimum fuel-use altitude/speed characteristics. Current constraints would not allow the 2% to 3% block fuel reduction potential of these techniques to be included for the candidate TAC/Energy concept. Other possibilities may exist.

State of Readiness.—The necessary definition of the current and planned future ATC system and potential aircraft capabilities are available to perform the necessary evaluation, with fuel conservation as a prime driving force.

Recommended Action.—It is recommended that an initial study be conducted considering all facets of aircraft/ATC interaction over the complete trip profile. This should include the implication of fleet operations, considering different aircraft designed for specific stage lengths and planned changes to the ATC system. The study could be conducted by an airframe manufacturer in cooperation with airlines and Government agencies, under DOT or NASA sponsorship. The study should include at least the following activities:

1. Survey of industry, airlines, and DOT and NASA fuel conservation studies for potential fuel-saving operational techniques

2. Use, as appropriate, of models to determine fuel-saving payoffs of candidate techniques as functions of ATC and airplane system parameters

3. Identification of promising operational techniques

4. Identification and recommendation of aircraft and ATC system technology advances necessary for the best use of fuel-saving operational techniques

Cost and Schedule.—A 12-month program estimated to cost $300 000 is recommended.

8.3.4.2 Fuel Reserves

Potential Payoff.—During the sensitivity studies (sec. 4.2), it was determined that a significant amount of fuel is consumed because of the amount of reserve fuel required by current regulations. At the 5556-km (3000-nmi) design range, reserve fuel equivalent to approximately 25% of the total block fuel is required. To correlate the effect on fuel usage (although undoubtedly not practical), if the reserves could be reduced to 50% of current rule requirements, a saving of 6% total block fuel could be realized for the design range mission. For a 1296-km (700-nmi) stage length, where reserve fuel is equivalent to block fuel, a 7% fuel saving could be realized.

State of Readiness.—Necessary data on current and future ATC provisions, weather, airports and airways, and aircraft capabilities are available to determine the potential for possible revision to rules that control the amount of required fuel reserve. Such rules have been in effect for several years and deserve reevaluation in light of the current and predicted technical and operational environments that govern their content.

Recommended Action.—It is recommended that a study be conducted involving an airframe manufacturer, airlines, and governmental agencies. The study should consider the following as a minimum:

1. Isolation of the factors that supported definition of the current rules

2. Correlation of technical and operational conditions that affect factors identified in item 1 initially, at the current time, and as projected in the future

3. Determination if conditions that would affect reserve have or are projected to change

4. Determination of technical advancements that, if made available, would allow desirable rule changes

Cost and Schedule.—A 6-month study funded at $450 000 is recommended.

8.3.4.3 Short Range Aircraft

Potential Payoff.—Evaluation was made of transport aircraft fuel consumption as a function of payload capacity and stage length. This revealed that nearly 60% of the fuel is consumed by all types of aircraft operating over stage lengths of less than 2880 km (1500 nmi). Most of those aircraft are of the less than 100- to 200-passenger-capacity type. The cruise speed of aircraft operating over 370- to 1110-km (200- to 600-nmi) stage lengths is from M = 0.1 to 0.15 less than for the design range considered by this study. The fuel used during the climb/descent portions of those shorter missions is, however, considerably greater.

Because of the altitude, speed, effect of reserves, climb, and other characteristics of the short-range aircraft, desirable fuel conservation features and the need for R&T will be different in several design areas, as compared to the longer design range concept considered in this study. In particular, at least the propulsion cycle and wing geometry of such aircraft are expected to be different. Weight is expected to be more important than aerodynamic efficiency. Because such short-range aircraft consume a large portion of the aviation fuel, their optimum design characteristics and need for R&T should be evaluated.

State of Readiness.—The techniques and background data needed to evaluate the special characteristics of short-range aircraft are available. Although a short-range study was sponsored by NASA/Ames (contract NAS2-6995), that study concentrated on a quite short field length aircraft. Although possibly adaptable to future conditions, the short field lengths are not consistent with the probable majority of short-range fleet operations.

Recommended Action.—It is recommended that a 9-month study funded at $250 000 be issued with the objective of defining the unique technical and economic characteristics of short-range transports when operating in a fuel shortage and/or high-cost environment.

APPENDIX A

ENGINE SUBCONTRACTOR REPORT

Portions of the complete final report submitted by Pratt & Whitney Aircraft in support of this study are presented. Those parts of the report considered most pertinent to the airplane studies using unconventional engines are included.

INTRODUCTION

P&WA support of the Boeing effort included the following tasks:

1. Review the cycle and installation assumptions and the performance and weight trends of the Boeing baseline turbofan engines.

2. Suggest advanced engine concepts that could provide fuel conservation opportunities, and coordinate with Boeing the selection of three of these for further study.

3. Provide technical support to Boeing in simulating the performance characteristics of the selected advanced engines.

4. Estimate the performance, dimensions, weight, and price of each of the selected advanced engines.

ENGINE PERFORMANCE

Baseline Cycles

The baseline cycles used by Boeing in the study consisted of a family of conventional turbofans covering a range of bypass ratios, at one level of overall pressure ratio and turbine temperature. These cycles were used as a reference point in evaluating the merits of the advanced cycles. Boeing provided P&WA with the performance of this family of engines along with the component assumptions that were used to calculate the performance. Based on the cycle definitions and component assumptions used by Boeing, the performance of the baseline cycles could be very closely approximated by P&WA. The small difference in level (less than 1%), which was later resolved to be due to a difference in the method of handling turbine cooling air, was considered not important since the trends were consistent. This comparison ensured that Boeing and P&WA were calculating cycle performance consistently.

Because of the possibility that the procedure used to define and rate engine cycles may be different than the method used by Boeing, P&WA established its own base turbofan cycle as a starting point from which to define the advanced cycles. The performance increments for the advanced cycles relative to base cycles were established by P&WA, and Boeing applied these increments to their own base cycles to achieve the same relative performance change for advanced cycles.

The P&WA base cycle is defined as follows:

FPR	1.6
BPR	6.1
OPR	25
Maximum TIT	1315°C (2400°F)

For comparison, the Boeing bypass 6 cycle is also shown:

FPR	1.66
BPR	6.0
OPR	24
Maximum TIT	1282°C (2340°F)

Turboprop

The turboprop cycle selected for the study was based on the same component performance and technology level as the base turbofan. Since the base turbofan had a benefit in OPR from the fan root supercharging which was not available for the turboprop, the overall pressure ratio was reduced to 20 to 1 for the turboprop. This requires an increase in high compressor pressure ratio from 17 for the base turbofan to 20 for the turboprop, which is achieved by adding two stages to the rear of the compressor. The cycle definition of the turboprop is given in the following list:

OPR	20
Maximum TIT	1315°C (2400°F)
Prop characteristic used for thrust sizing	Hamilton Standard PDB 6101, Generalized Method of Propeller Performance Estimation 140 AF/0.15 C_{L_i}/4 blades
Diameter	5.9 m (19.4 ft)
Tip velocity	213 m/s (700 ft/sec)

Performance for the turboprop cycle is provided in table A-1.

High Overall Pressure Ratio Turbofan

Before selecting a level of pressure ratio for a high overall pressure turbofan, a trend study was completed which showed the benefits to be gained for increases in overall pressure ratio. The following levels of component technology were considered in making the study:

1. Component Technology Consistent With the Base Turbofan: For this case the turbine cooling air was increased as overall pressure ratio increased in order to maintain a constant turbine airfoil metal temperature. High turbine efficiency was penalized for the increased cooling air.

2. Improved Turbine Cooling Technology: For this case the level of turbine cooling air was held constant at the base turbofan level as OPR increased. This case would be

Table A-1.—Summary of Engine Cycles

Cycle definition	Base turbofan	Turboprop[a]	High OPR turbofan	Variable pitch fan (variable AJD)
FPR	1.6	—	1.6	1.4
BPR	6.1	—	6.4	8.4
OPR	25	20	40	25
Max TIT, K (° F)	1 590 (2 400)	1 590 (2 400)	1 590 (2 400)	1 590 (2 400)
Performance				
SLS T/O FN, N (lb)	63 000 (14 160)	77 300 (17 380)	63 200 (14 200)	66 100 (14 850)
FN lapse to 0.3 M, %	-29%	-34%	-29%	-35%
Max Cr., 30 000 ft				
0.8 M FN, N (lb)	16 500 (3 700)	11 800 (2 650)	16 500 (3 700)	16 500 (3 700)
TSFC	Base	+11%	-5.1%	-2.1%
0.7 M FN	16 600 (3 730)	15 600 (3 500)	16 700 (3 760)	16 600 (3 730)
TSFC	Base	-21%	-5.2%	-2.4%
Design Point Airflows				
WAT_2, kg/sec (lb/sec)	279 (615)	25.4 (56)	281 (619)	362 (798)
Technology				
Components	1980	1980	1980	1980
Turbine cooling	1980	1980	1985-1990	1980
Propeller (0.7 M design)	—	140AF/0.15$C\ell_i$	—	—

[a]140 AF/0.30$C\ell_i$ propeller was used for 0.6 M cruise with performance as shown in section 4.4.3.6.

representative of either more effective turbine cooling, increased metal temperatures, or cooled turbine cooling air.

For this trend study the fan pressure ratio, high compressor polytropic efficiency, and nozzle jet velocity were held constant as the overall pressure ratio was increased. This resulted in a decreasing bypass ratio as overall pressure ratio increased.

At the base turbofan level of technology it was found that the optimum overall pressure ratio is about 33 to 1 and the TSFC improvement is only 1.3%. At higher pressure ratios, the increase in turbine cooling and high turbine efficiency penalty due to more cooling offset the pressure ratio effect and TSFC gets poorer. However, the case where turbine cooling air flow was held constant at the base turbofan level shows TSFC improving by about 3% up to pressure ratios of 40 to 1 and above.

Based on the results of this study it was decided that increasing OPR alone, without a turbine cooling technology improvement, did not offer a significant enough improvement in fuel consumption. For this reason, advanced turbine cooling technology was assumed to provide a 50% reduction in cooling flow at 40 to 1 pressure ratio relative to the base 25 to 1 engine. This would require extensive advances in materials, cooling configurations, and/or cooled cooling air. The reduction in turbine cooling air results in an increase in BPR relative to the base cycle.

Variable-Pitch Fan Turbofan

A fan pressure ratio of 1.4 at the aero design point was selected for the VPF turbofan as a reasonable compromise between:

- Higher FPR, which the baseline studies indicate would provide better airplane performance

- Lower FPR, which previous studies have indicated would show more operational advantage for the variable-pitch feature

Engines with low fan pressure ratios have a fan stability problem at sea level static since the fan operating line moves up relative to altitude cruise, because of the unchoking effect of the fan nozzle. In fixed-pitch fans, this effect can be controlled by opening up the fan duct nozzle to lower the fan operating line. This requires either a two-position nozzle, which results in an installation penalty, or a permanent lowering of the cruise operating line, which results in a performance penalty. The variable-pitch fan offers the possibility of providing increased sea level stability through a fan pitch change. However, evaluation of the 1.4 pressure ratio fan indicates that the variable-pitch capability does not provide enough surge margin control at sea level to completely eliminate the need for one of the other methods of operating line control. For this study a two-position nozzle was selected for takeoff and cruise operation. A third position of the nozzle would be required for reverse thrust.

Performance of the variable-pitch turbofan is shown in table A-1.

ENGINE INSTALLATION

This section summarizes the weight information provided for the base turbofan and the advanced engines.

WEIGHT

Baseline

Turbofan.--The recommended specific weight (weight/airflow) band versus bypass ratio, shown in figure A-1, assumes that the engines will be in service by 1980.

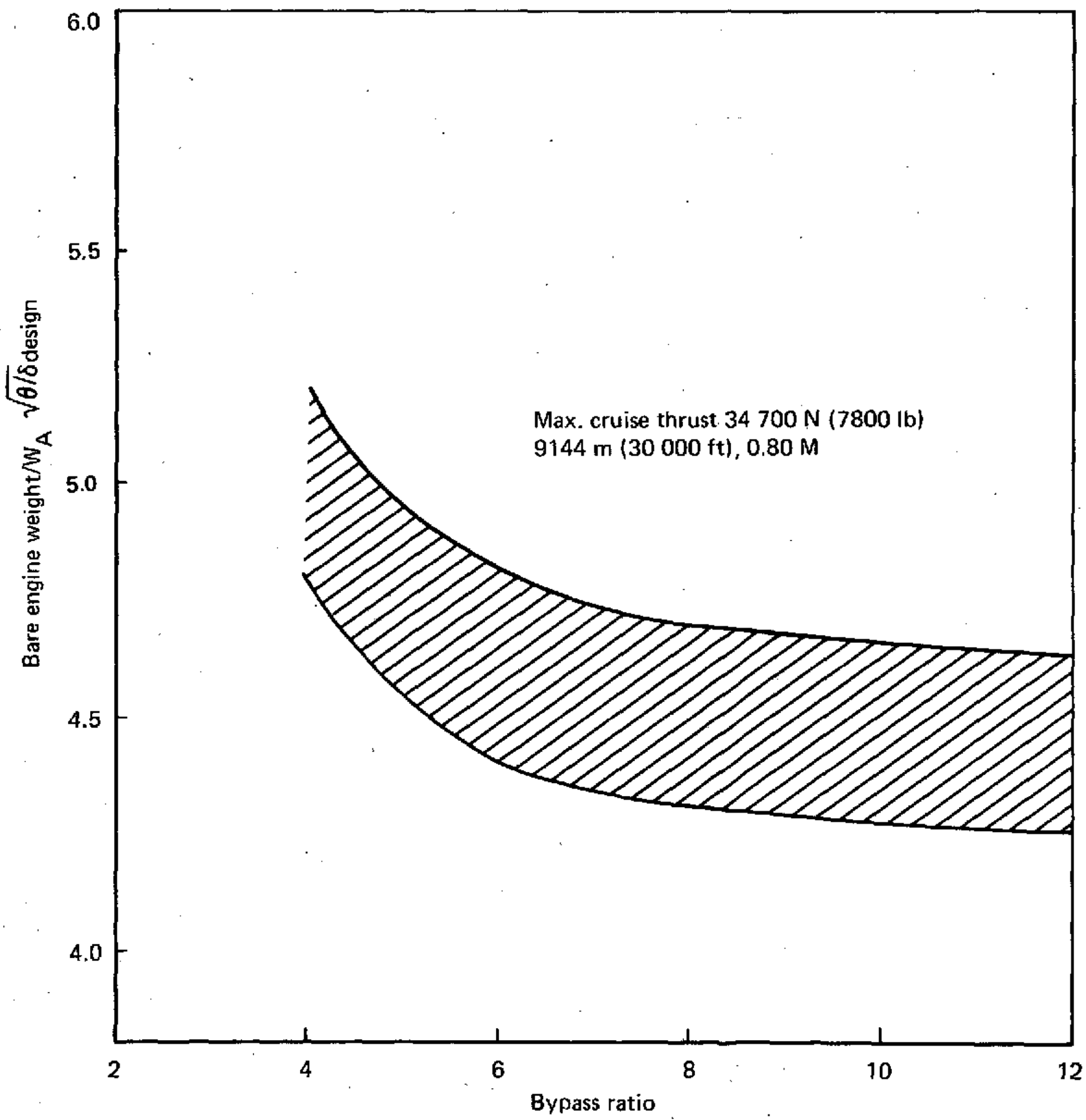


Figure A-1.—Specific Weight of Turbofan Engines

Turbofan Weight Scaling With Airflow.—The turbofan bare engine weight scaling curve of figure A-2 is independent of bypass ratio and overall pressure ratio.

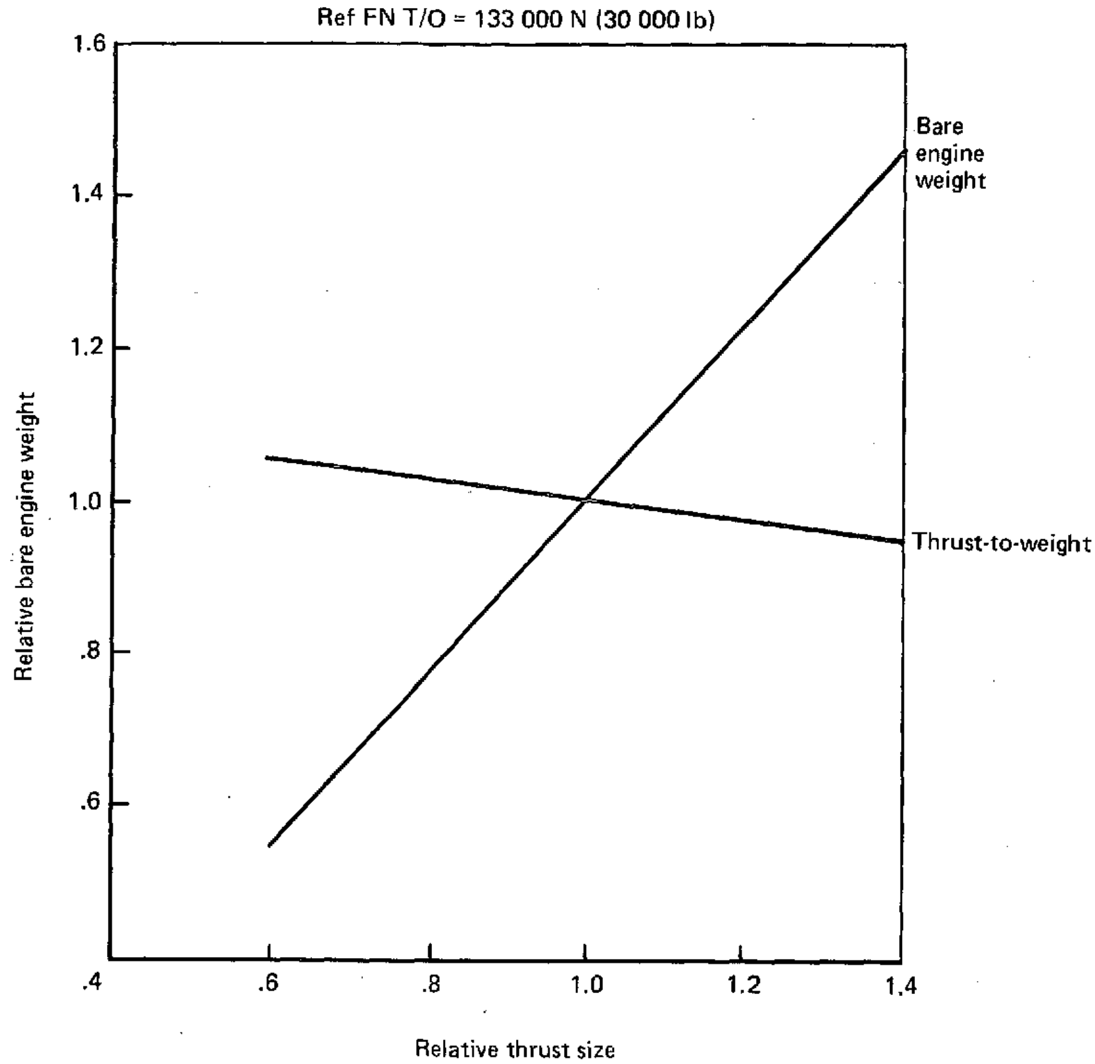


Figure A-2.—Weight/Thrust Scaling Turbofan Engines

Turbofan Weight Variations With Overall Pressure Ratio.—For constant technology, the specific weight is essentially constant for a given bypass ratio engine for overall pressure ratios of 20 to 1 to 40 to 1. This conclusion is based on results of previous preliminary concept studies.

Turboprop

Turboprop Versus Turbofan Weight.—The base turbofan's weight includes the fan, cases, gas generator, controls, and accessories, but no installation (i.e., cowl, nozzles, etc.). The turboprop's weight includes only the gas generator, propeller drive turbine, controls, and accessories. Propeller, gearbox, and installation are not included.

The turboprop has an overall pressure ratio of 20 to 1, as opposed to 25 to 1 OPR for the base turbofan. Since the technology levels are assumed constant for these two cycles, the turboprop must add two stages to the rear of the base turbofan's high compressor to partially offset the loss of fan supercharging.

The turboprop weight is estimated to be 1.25 times the base turbofan's weight, assuming equal inlet "core" airflow sizes at 30 000 feet, Mach 0.7, maximum cruise.

Propeller and Gearbox Weight.—Propeller preliminary weight estimates were summarized as follows, based on Hamilton Standard data:

$$\text{Weight} = 180\left[\left(\frac{D}{10}\right)^{1.85}\left(\frac{B}{4}\right)^{0.7}\left(\frac{AF}{100}\right)^{0.6}\left(\frac{ND}{20\,000}\right)^{0.5}(M+1.0)^{0.5}\left(\frac{SHP/D^2}{10}\right)^{0.12}\right]$$

where

D	= diameter, feet
B	= number of blades
AF	= activity factor per blade
N	= propeller maximum speed, rpm
M	= flight Mach number at design condition
SHP	= design SLTO standard day power, horsepower

The weight assumes fixed camber, lightweight fiberglass blades with an integral gearbox type hub and includes the spinner, control, de-icing and oil, but not the gearbox.

The gearbox weight estimates were also generalized on Hamilton Standard data, as

$$\text{Weight} = 0.075\ (Q)^{0.84}$$

where Q is the maximum continuous output torque in foot-pounds. The following assumptions apply to this gearbox weight formula:

- Two-stage gearbox with one planetary set and offset parallel drive
- Reduction ratios from 10 to 1 to 14 to 1
- No provision included for cross-shaft drive, declutching, or special accessory drives

High Overall Pressure Ratio Turbofan

It was noted that, for constant technology, there is essentially no specific weight (weight/airflow) variation with overall pressure ratios ranging from 20 to 1 to 40 to 1. However, Boeing requested information on a high OPR engine with a more advanced technology in the areas of either high-pressure turbine materials and coatings or cooling scheme effectiveness or both, relative to the base turbofan. This resulted in the 40 to 1 overall pressure ratio turbofan with 1985-90 inservice cooling technology for which P&WA provided information to Boeing.

The advanced technology permitted a turbine cooling airflow reduction for the 40 to 1 OPR turbofan, relative to the base turbofan. This cooling airflow reduction resulted in an increase in turbine efficiency and, at constant combustor exit temperature, a decrease in the cooling air dilution effect on high-pressure turbine exit temperature. Bypass ratio had to be increased to offset the effects of the efficiency improvement and decrease in dilution effect. The increase in BPR caused an increase in engine total airflow, resulting in a thrust increase at cruise. Therefore, the entire high OPR turbofan with advanced cooling technology was scaled down to maintain constant cruise thrust. This scaling, in effect a scaling down of the gas generator, resulted in a 1% weight reduction for the high overall pressure ratio turbofan relative to the base turbofan.

Variable Pitch

The variable-pitch fan was assumed to use shroudless advanced composite fan blades rather than titanium blades, as in the shrouded fixed-pitch fan. The weight saving of the composite fan blades, plus the resulting saving in fan disk, shaft, and containment weight approximately offsets the weight increase due to the pitch change mechanism, lower aspect ratio, and higher hub-tip ratio of the variable-pitch fan. This results in the estimate of no weight difference between the fixed- and variable-pitch engines.

Summary

The bare engine weight results are summarized in the following list. Each engine is sized to provide 16 500 N (3700 lb) of thrust at 9144 m (30 000 ft), Mach 0.8, maximum cruise (turboprop sized for 15 600 N (3500 lb) of thrust at 9144 m (30 000 ft), Mach 0.7, maximum cruise):

Engine	Relative Weight
Base turbofan	1.0
Turboprop gas generator	0.81
High OPR turbofan	0.99
VPF	1.27

ADVANCED TECHNOLOGY REQUIREMENTS

Baseline

The definition of the base turbofan (1980 inservice technology) excludes the need for any particular advanced technology requirement.

Turboprop

Gas Generator.—The gas generator and propeller drive turbine are based on technology levels consistent with the base turbofan; therefore, no specific advanced technology requirements exist for the gas generator or propeller drive turbine.

Gear.—Advanced high-powered gearing concepts should be investigated, and specific tests on new technologies such as high contact ratio gears should be conducted. System health diagnostics (e.g., multigraduated mesh metallic particle sensors, vibration/acoustic analyzers) need to be developed. The potential of advanced lube system components such as integral centrifugal air-oil separators and centrifugal self-cleaning filters should also be investigated. Heat rejection and efficiency must be considered in the design of any advanced high-powered gears.

Propeller.—Advanced composite blade technology needs to be developed, and design investigations into advanced maintenance concepts should be conducted. In addition, the aircraft-engine-propeller integration has to be optimized.

High OPR Turbofan

Further improvements in advanced technology are required for the high OPR engine relative to the lower OPR base engine because of the higher exit temperature, smaller airfoil sizes, and advanced cooling technology (i.e., 1985-90 inservice engines) of the 40 to 1 OPR turbofan. These further improvements are:

- Airfoil materials with higher metal temperature capability
- Improved temperature airfoil coatings to go along with the higher airfoil metal temperature
- Improved cooling system effectiveness
- Further advances in clearance control, especially at the rear of the high compressor and the first stage of the high turbine where the airfoil spans are smaller than usual
- Improved disk materials such as: (1) high-temperature titanium to minimize the use of more expensive nickel base alloy high-compressor disks and (2) high-strength, improved low-cycle fatigue (LCF) nickel base alloys to provide reduced weight and increased life of high turbine disk configurations
- Reduced NO_x emissions technology, since NO_x increases as pressure ratio and compressor exit temperature are increased with today's technology
- Improved sealing technology, due to the higher pressure differential across seals in the burner-high turbine area, to reduce leakages
- Improved burner liner materials, to accommodate the higher burner inlet temperature without degrading burner durability or performance

VPF

Gas Generator.—Since the gas generator and fan drive turbine are based on technologies consistent with the base turbofan, there are no advanced technology requirements for the VPF's gas generator and fan drive turbine.

Variable-Pitch Fan.--Composite fan blade technology must be developed in areas such as improved foreign object damage (FOD) resistance and low-cost fabrication methods. The reverse thrust/reverse flow air inlet configuration should be optimized, and concepts for variable fan duct exit areas as applicable to high-bypass-ratio designs need to be investigated.

Gear.--The advanced technology gear requirements noted for the turboprop are also applicable to the VPF.

General

Further advances in the following items, although not essential, would improve all engines including the base turbofan:

- Higher pressure ratio per stage capability at good efficiency levels, for fans, compressors, and turbines
- Improved turbine airfoil, endwall, and secondary cooling capability
- Improved compressor, burner, and turbine durability to minimize performance degradation and maintenance costs
- Improved clearance controls throughout the engine, to improve component performance and reduce leakages and secondary flows
- Improved materials such as composite fan blades, high-temperature titanium for compressor disks, high-strength nickel base alloys for turbine disks, and high-temperature turbine airfoil materials and coatings
- Shorter burners with improved performance and low emissions technology
- Fabrication technology including reduced cost turbine airfoils, small cooling hole technology, near-net and net-shape disks, large cast cases, lightweight structures, and fabricated sheet metal cases
- Improved bearings; improved seals including abradable/abrasive seal technology on airfoil/cases for tighter clearance control
- Improved accessories including an electronic control to improve performance, hot section life, control maintenance, and reliability

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Standard Delay

	CWB$_{LRC}$*	CWB-E	ATT-E	TAC-E	TAC/Energy
DOC, $/trip					
1852 km (1000 nmi)					
5.8¢/ℓ (22¢/gal) fuel	Not calculated				
Crew		700.78	623.44	623.33	692.38
Fuel		837.06	839.34	869.28	601.66
Maintenance		704.11	638.67	874.07	840.85
Insurance		136.25	116.76	131.20	124.25
Depreciation		960.49	822.77	926.66	876.35
Total	3402.13*	3338.69	3040.98	3424.54	3135.49

DOC not calculated by ATA formula (see sec. 6.2.3.1)

Block fuel, kg (lb)	CWB$_{LRC}$*	CWB-E	ATT-E	TAC-E	TAC/Energy
1852 km (1000 nmi) 55% LF	11 975* (26 400)	11 340 (25 000)	11 340 (25 000)	11 793 (26 000)	8 165 (18 000)
5556 km (3000 nmi) 100% LF	38 465* (84 800)	35 562 (78 400)	32 749 (72 200)	33 158 (73 100)	24 313 (53 600)

Block time, hr	CWB$_{LRC}$*	CWB-E	ATT-E	TAC-E	TAC/Energy
1852 km (1000 nmi)	2.473	2.473	2.267	2.267	2.523
5556 km (3000 nmi)	6.796	6.796	6.207	6.207	6.873

*Estimated at long-range cruise conditions

Expected Delay

	CWB$_{LRC}$*	CWB-E	ATT-E	TAC-E	TAC/Energy
DOC, $/trip					
1852 km (1000 nmi)					
6.8¢/ℓ (22¢/gal) fuel	Not calculated				
Crew		838.28	760.94	623.33	692.38
Fuel		947.47	985.78	869.28	601.66
Maintenance		783.37	738.59	874.07	840.85
Insurance		136.25	118.76	131.20	124.25
Depreciation		960.49	835.77	926.66	876.35
Total	3740.00*	3665.86	3439.84	3424.54	3135.49

DOC not calculated by ATA formula (see sec. 6.2.3.1)

Block fuel, kg (lb)	CWB$_{LRC}$*	CWB-E	ATT-E	TAC-E	TAC/Energy
1852 km (1000 nmi) 55% LF	13 585* (29 950)	12 882 (28 400)	13 381 (29 500)	11 793 (26 000)	8 165 (18 000)
5556 km (3000 nmi) 100% LF	40 642 (89 600)	37 988 (83 750)	34 994 (77 150)	33 158 (73 100)	24 313 (53 600)

Block time, hr	CWB$_{LRC}$*	CWB-E	ATT-E	TAC-E	TAC/Energy
1852 km (1000 nmi)	2.973	2.973	2.767	2.267	2.523
5556 km (3000 nmi)	7.296	7.296	6.707	6.207	6.873

*Estimated at long-range cruise conditions

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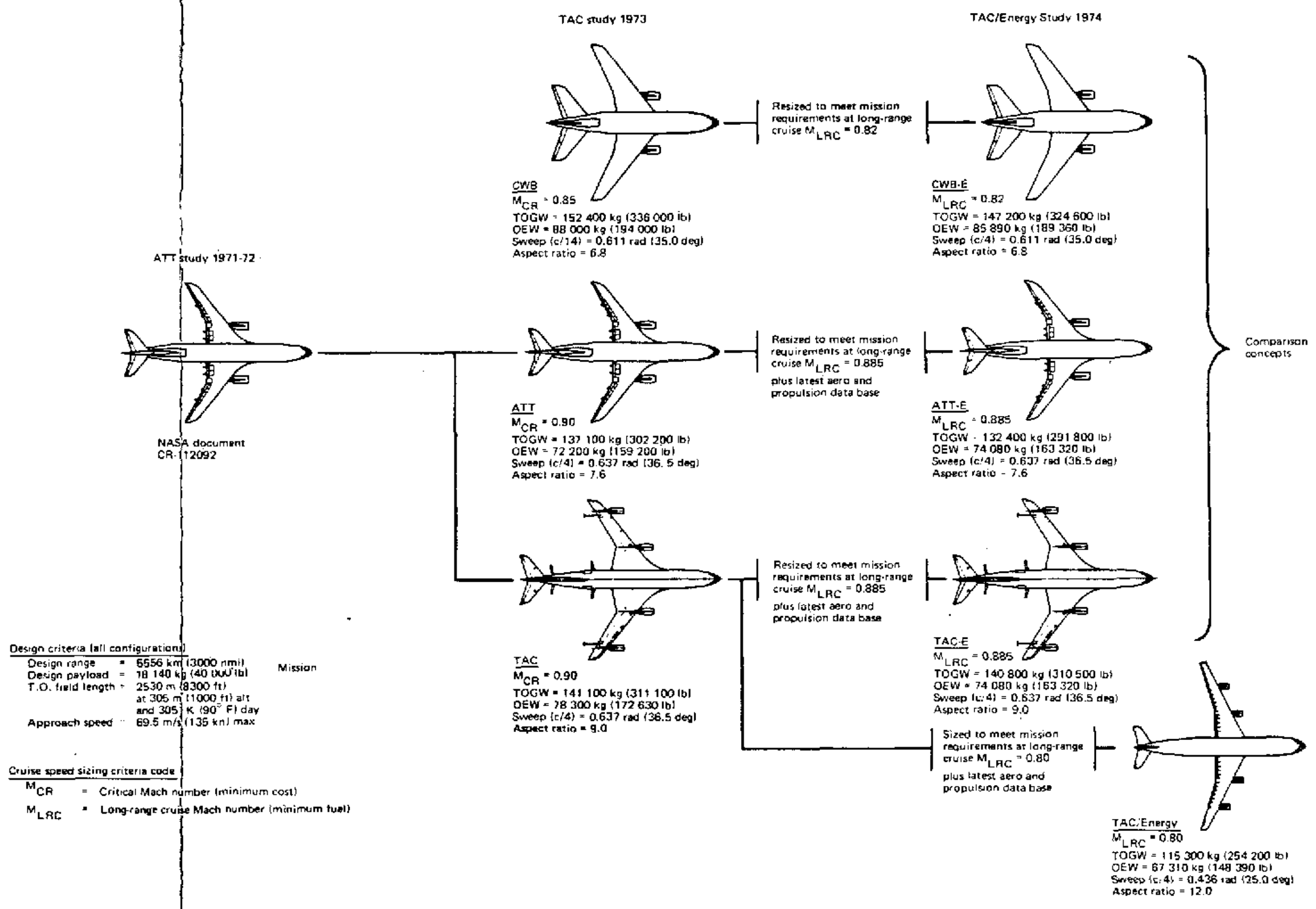

TAC/Energy Concept and Comparison Concepts Evolution

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